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Assessment of French artificial reefs: due to limitations of research, trends may be misleading

Anne Tessier · Patrice Francour · Eric Charbonnel · Nicolas Dalias · Pascaline Bodilis · William Seaman · Philippe Lenfant

Abstract Artificial reefs have been deployed in France since 1968 with the principal objective of enhancing success and continuity of artisanal fishing. Over 50 % of the volume of reef material has been deployed since 2000. Because of significant expansion of reef construction and availability of new research results concerning their performance since the late 1990s, we examined status and trends of French artificial reefs. Since the review of Barnabé et al. (Artificial reefs in European seas, 2000), 35 reports have been published and are analyzed here. Fish assemblages on artificial reefs have been the focus of ecological research, with emphasis on species richness and abundance. Fish production has been associated with the age of artificial reefs and the reef's structural complexity. The perception of stakeholders toward artificial reefs is a notable area of investigation. Economic studies are absent. Other developments in French artificial reefs over the last 10–15 years include the discontinued use of waste materials in reef construction, more directed design of reef structure, and the inclusion of additional objectives concerning biodiversity and recreation. Recommendations here include development of long-term ecological studies of artificial reefs and the evaluation of fishery production, including issues such as trophic dynamics, ecological connectivity of habitats, and socio-economic studies.

A. Tessier (✉) · N. Dalias
SEANEO, 11 Rue Louis Esparre, 66100 Perpignan, France
e-mail: anne.tessier2@wanadoo.fr

A. Tessier · P. Lenfant
Université Perpignan Via Domitia, 52 Avenue Paul Alduy, 66860 Perpignan, France

Present Address:
A. Tessier
INRA-UMR CARRTEL, 75 avenue de Corzent, 74203 Thonon les Bains, France

P. Francour · P. Bodilis
Université Nice-Sophia Antipolis, EA 4228 ECOMERS, Parc Valrose, 06108 Nice, France

E. Charbonnel
Parc Marin de la Côte Bleue, Observatoire plage du Rouet, 31 Avenue Jean Bart, BP 42, 13620 Carry-le-Rouet, France

W. Seaman
Fisheries and Aquatic Sciences, University of Florida, Montreat 2857, USA

P. Lenfant
CNRS, CEntre de Formation et de Recherche sur les Environnements Méditerranéens, UMR 5110, 52 Avenue Paul Alduy, 66860 Perpignan, France

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Introduction

Artificial reefs (ARs) are used worldwide to conserve, restore and enhance coastal ecosystems and their allied ecological services. Artificial reefs have the form and function of a *"submerged structure placed on the seabed deliberately, to mimic some characteristics of a natural reef"* (Jensen, 1998; UNEP, 2005). Along the shorelines of the Atlantic Ocean and Mediterranean Sea of Europe, by 2000, virtually all nations had deployed ARs for management of fisheries, protection of benthic habitat, restoration of ecosystems, and research (Jensen, 2002). The largest developmental, experimental, and deployment efforts have occurred off Italy, Spain, Portugal, and more recently, off France (Fabi et al., 2011).

Historically, some of earliest AR deployments in Europe occurred off France, starting in 1968 (Barnabé et al., 2000). During the last decade, several new projects have been implemented, including what arguably may be the largest project of its kind in Mediterranean waters (Charbonnel et al., 2011). The present work reviews recent advances and applications of AR technology in French coastal waters, with an emphasis on research undertaken over the last 15 years concerning the ecological structure and function of artificial reefs and their role in natural resources management and science. The effectiveness of new reef designs to produce fish biomass and increase biodiversity is assessed in the context of how the reefs improve the performance and acceptance of artificial reefs in fishery and ecosystem management (Bortone et al., 2011). To evaluate the research on artificial reefs off France since 1990, we include comparisons with the earlier evaluation provided by Barnabé et al. (2000).

Methods

Information from 45 publications (10 before 2000, 35 dated 2000 and later) concerning ARs in France (and overseas territories) was compiled through a search of Internet sources and contact with 12 French experts (10 replies). The search of the Internet included use of ISI Web of Science and Google Scholar with combination of related topics, such as artificial reef*, monitoring*, and France*. ARs of the Principality of Monaco are excluded from this review. It is noteworthy that funding for artificial reef construction by the European Union requires monitoring, so that in recent years the body of literature concerning French reef performance has increased about three-fold compared to the decades before 2000 (Fig. 1). As used here, "publication" refers to all formats of scientific articles, including peer-reviewed journal papers, unpublished and internal contract reports, and graduate student theses and dissertations. Our emphasis was on the period subsequent to the review made by Barnabé et al. (2000) focused on the period between 1975 and 1998. For both periods, most documents were limited circulation reports, such as those submitted by an investigator to a contracting organization. More recently, the proportion of documents that are peer-reviewed has increased (Fig. 1).

Part of this review deals with immersion costs. Thus, the calculation of AR construction and deployment costs was done by dividing the total cost of the AR project (found in the reports) by the immersed volume of the artificial reef. Costs are given in updated Euros-per-m^3 to take account of inflation with 2010 used like base-year.

Trends in artificial reef design and deployment practices in France

Trends and innovations since the late 1990s in AR deployment in France include the discontinued use of waste materials in AR construction, the shift to the intentional design of reef structure, and the nearly exclusive use of concrete in the fabrication of AR modules. Additional changes in the objectives for ARs include non-artisanal fishing purposes, with designs (architecture of modules and arrangement between modules) increasingly based upon results of scientific studies that addressed the life history attributes of designated species and assemblages. There was increased funding for construction from the European Union along with increased levels of monitoring and evaluation of reef performance and more peer-reviewed publication of findings. One measure of the effects of recent AR deployment in European Atlantic

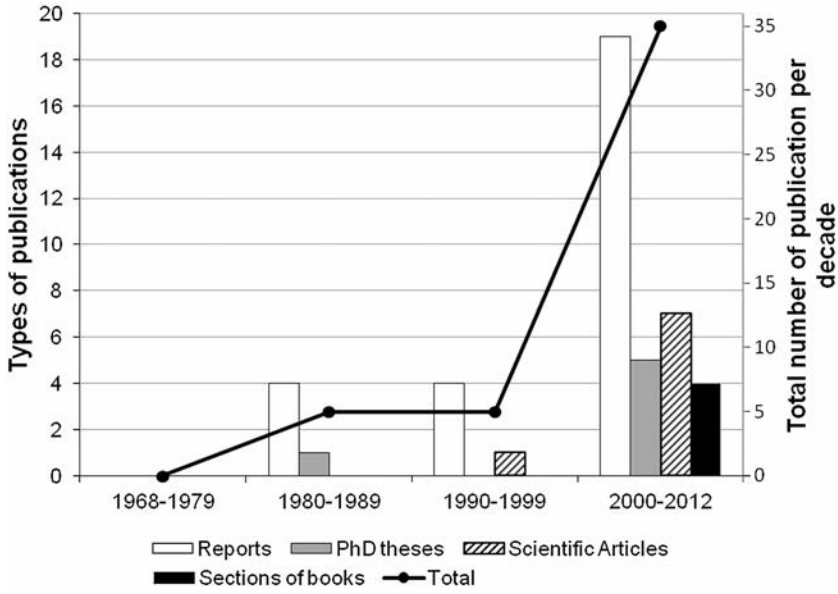


Fig. 1 Total number of publications and number of publications by types on artificial reefs in France by decade

countries, which also applies obviously to the French Mediterranean, states, *"most of the reefs constructed over the last decade have been carefully planned, subjected to environmental impact assessments, and are being carefully monitored. Perhaps as a result, relatively few negative impacts have been reported"* (Jackson, 2009).

Location and deployed volumes

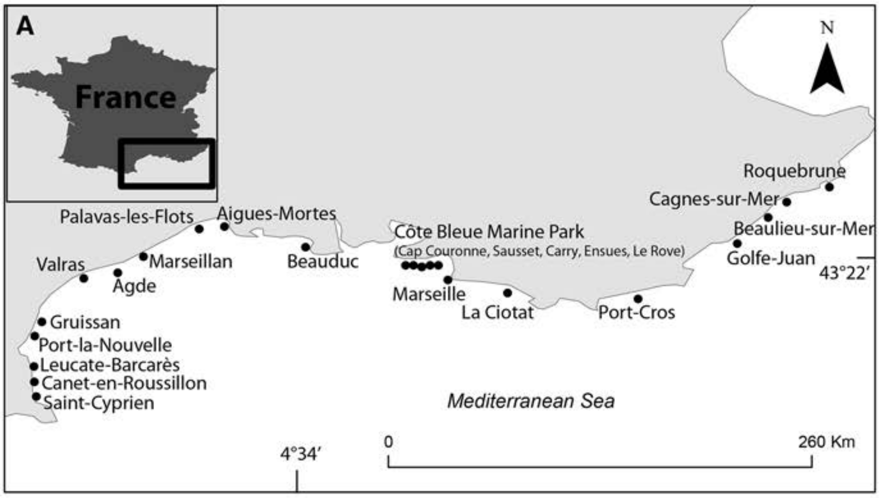
Of the 33 AR sites in France (Fig. 2; Table 1; note that Côte Bleue Marine Park site includes five lesser sites), 20 were established before 1997–2000 and were included in the review of Barnabé et al. (2000) who described locations, objectives, and construction of the earlier period 1968–1998. Six of the 20 ARs established before 2000 have received additional materials after 2000. Thirteen other ARs were built completely between 2000 and 2009 (France, Corsica, Reunion Island and Martinique).

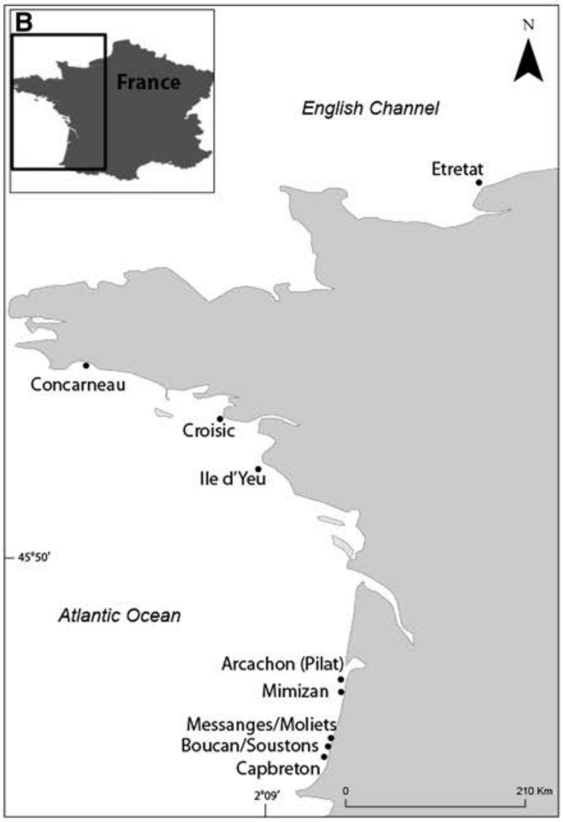
Since the onset of French reef construction along the Mediterranean (in 1968) and Atlantic (in 1970) coasts, over half (52 %) of the total volume of AR material (93,982 m^3) used has been deployed since 2000 (Fig. 3). Previously, the most active period for the construction of artificial reefs occurred during the 1980s with 38 % of AR volume deployed. Typically AR sites are near the coastline, at depths less than 30 meters. The sizes of ARs in France are indicated in Table 1.

The Provence-Alpes-Côted'Azur (PACA) and Languedoc-Roussillon regions along the Mediterranean coast account for 92 % of AR volume, with 50,060 and 37,575 m^3 of material, respectively (Table 1). A new project in Marseille is the largest, to date, in Mediterranean Sea with a volume of 27,300 m^3 deployed only on 220 ha (Charbonnel et al., 2011). This size makes this latest project roughly 10 times larger than any other French AR deployment.

Artificial reefs on the Atlantic coast include five new, relatively smaller sites built since 2000 (compared to four larger ARs on the Mediterranean) and this represents 5 % of the total volume of material deployed nationally. The difference in the amount of construction between the Mediterranean and Atlantic coasts reflects the relatively unstable benthic conditions of the latter area. The Atlantic is characterized by a gently sloping continental shelf substratum of mobile sand, and exposure to westerly winds which generate long swells which could damage ARs (Barnabé et al., 2000). Furthermore, this difference in amount of reef construction could also be due to a lesser demand among Atlantic stakeholders, or because local artisanal fishing practices differ from the French Mediterranean Sea. Finally, AR deployments in Corsica and in the overseas departments and territories are recent (the last decade), and represent 1.5 % of the total volume in France (Table 1).

Fig. 2 Location of artificial reefs areas on the French coasts of **A** The Mediterranean Sea and **B** Atlantic Ocean. (Names in brackets refer to the designation of these same reefs in Barnabé et al. (2000), Provence-Alpes-Côte-d'Azur region includes all sites between Roquebrune and Beauduc and Languedoc-Roussillon region all sites between Aigues-Mortes and Saint-Cyprien





Objectives of artificial reefs

Artificial reefs generally conform to the objectives of the 1976 Barcelona Convention, which addresses *"structures specifically built for protecting, regenerating, concentrating and/or increasing the production of living marine resources, whether for fisheries or nature conservation. This includes the protection and regeneration of habitats"* (Jensen, 1998; UNEP, 2005). The principal and continuing objectives for artificial reefs in France are to sustain artisanal fisheries. It is the objective of 80 % of ARs deployed since 1980.

Table 1 Characteristics of artificial reef sites deployed in France; No Data (−); the first level of classification of the table is the region, the second is the order of appearance in the time of RAs new sites in the region

Deployment area	Year of deployment	Description of artificial reefs	Dumped volumes (m^3)	Dpth of deployment (m)	Objectives	References
Provence-Alpes-Côte d'Azure (PACA)						
Roquebrune	1980/83	6 Modules of breeze blocks	48	22–39	Maintain artisanal fishing Protect marine habitat	Charbonnel (1990) and Charbonnel et al. (2001b)
	1985/87	590 Cubic reefs of 1 m^3 , 448 cubic reefs of 2 m^3, 252 cubic reefs of 1.4 m^3, 15 Bonnas	4,208	22–39		Charbonnel (1990) and Charbonnel et al. (2001b)
	1990	3 Thalamés, modification of 2 Bonnas containing breeze blocks,concrete elements	81	15–30		Charbonnel et al. (2001b)
Cagnes-sur-Mer	2009	6 Heaps of 7 piles of 3 concrete domes, 6 heaps of 3 piles of 2 concrete domes, 35 piles of perforated plate steel, 30 concrete plates with rope streamers	850	6–12	Maintain artisanal fishing Enhance biodiversity	Serre C. (pers. comm.)
Beaulieu-sur-Mer	1980/83	36 Modules of breeze blocks	288	22–39	Maintain artisanal fishing Protect marine habitat	Charbonnel (1990) and Charbonnel et al. (2001b)
	1985/87	561 Cubic reefs of 1 m^3, 96 cubic reefs of 2 m^3, 72 reefs of 1.4 m^3, 11 Bonnas	2,592	22–39		Charbonnel (1990) and Charbonnel et al. (2001b)
	1990/91	2 Thalamés, modification of 2 Bonnas within breeze blocks	78	15–30		Charbonnel et al. (2001b)
Golfe-Juan	1979/83	20,000 Old tires, 47 modules of breeze blocks	3,856	15–30	Anti-trawling Maintain artisanal fishing	Charbonnel (1990) and Barnabé et al. (2000)
	1985/88	588 Cubic reefs of 1 m^3, 284 cubic reefs of 2 m^3, 252 cubic reefs of 1.4 m^3, 14 Bonnas	3,721	15–30		Charbonnel (1990) and Charbonnel & Serre (1999)
	1989/91	3 Thalamés, modification of 3 Bonnas containing breeze blocks, tyres and concrete elements	127	15–30	Experimental test	Charbonnel & Serre (1999)
	1993	1 Wreckage	250	31	Protect marine habitat	Charbonnel & Serre (1999)
	1996	1 Wreckage	140	36		Charbonnel & Serre (1999)
Port-Cros	1985	35 Cubic reefs	35	–	Protect marine habitat Experimental test	Ody (1987), Ody & Harmelin (1994) Barnabé et al. (2000) and Charbonnel et al. (2001a)
La Ciotat	1986	190 Cubic reefs of 1.98 m^3, 3 Bonnas	856	33	Anti-trawling	Ganteaume (2000)
	1989	125 modules of 1.92 m^3	240		Maintain artisanal fishing	

Table 1 continued

Deployment area	Year of deployment	Description of artificial reefs	Dumped volumes (m^3)	Dpth of deployment (m)	Objectives	References
Marseille	2007/08	168 Heaps of 6 cubic reefs, 78 Mazes, 18 steel baskets, 30 heaps of rocky blocks, 18 floating ropes, 18 Fakir electric piles	27,300	18–33	Maintain artisanal fishing Experimental test Enhance biodiversity, habitats	Charbonnel et al. (2011) and Jouvenel & Roche (2011)
Côte Bleue Marine Park	1983	9 Alveolar pyramidals, 27 alveolar	225	15–23	Anti-trawling	Ody (1987) and Charbonnel et al. (2011)
(Five sites: see Fig. 1)	1985/89	390 Cubic reefs of 1.7 m^3, 90 cubic reefs of 2 m^3, 8 Bonnas, 83 rocky blocks, 100 Sea-rocks	2,628	15–55	Maintain artisanal fishing	Ody (1987) and Charbonnel et al. (2011)
	1996/97	87 Cubic reefs of 1.7 m^3, 91 Fakir electric piles	1,149	15–75	Experimental test	Charbonnel et al. (2011)
	2000/04	40 Négri columns, 12 Tripods, 6 Khéops	734	15–25		Charbonnel et al. (2011)
Beauduc	1989	440 Sea-rocks	654	–	Anti-trawling	Barnabé et al. (2000)
Total PACA			50,060			
Languedoc-Roussillon						
Aigues-Mortes	1999	109 Pipes, 25 heaps of 20 Sablas	1,623	7–22	Anti-trawling	CREOCEAN (2003) and Fourrier & Barral (2009)
	2006	144 Pipes, 80 heaps of 20 Sablas	2,400	15–20	Maintain artisanal fishing	Fourrier & Barral (2009)
Palavas-les-Flots	1968	15 Pipes, 7 T of old tires, 100 car wrecks, 50 rocky blocks	400	20–23	Maintain artisanal fishing Experimental test	Bombace (1989)
Marseillan	1992	60 Pipes	426	7–23	Anti-trawling	Collart & Charbonnel (1998) and Fourrier & Barral (2009)
	1996	45 Pipes	319	30–35	Maintain artisanal fishing	Collart & Charbonnel (1998) and Fourrier & Barral (2009)
Agde	1985	4 Bonnas, 9 heaps of 14 Comins	1,942	17–30	Anti-trawling	Bombace (1989) Fourrier & Barral (2009)
	1995	200 Pipes	1,420	9–20	Maintain artisanal fishing	Collart & Charbonnel (1998) and Fourrier & Barral (2009)
	2009	99 Pipes, 10 steel baskets, 2 Eco-reefs	1,083	9–32		Blouet et al. (2010)

Table 1 continued

Deployment area	Year of deployment	Description of artificial reefs	Dumped volumes (m^3)	Dpth of deployment (m)	Objectives	References
Valras	2006	34 Pipes, 9 steel baskets, 1 heap of 3 steel baskets	950	9–22	Anti-trawling Maintain artisanal fishing	Fourrier & Barral (2009) and Dalias et al. (2012)
Gruissan	1985	22 Bonnas, 22 heaps of 14 Comins	6,688	17–30	Anti-trawling Maintain artisanal fishing	Bombace (1989) and Fourrier & Barral (2009)
	2002	2 Heaps of Dalots and telegraph poles, 9 heaps of telegraph poles, 12 spiral staircases, 2 chaotic heaps	4,250	10-25		CREOCEAN (2004) and Fourrier & Barral (2009)
	2005	Same as in 2002 and 8 steel baskets with chaotic heaps	5,100	10–25		Fourrier & Barral (2009)
Port-la-Nouvelle	1980	Pipes, Old tires	3,000	–		Bombace (1989)
	1985	4 Bonnas, 4 heaps of 14 Comins	1,216	17–30	Anti-trawling Maintain artisanal fishing	Bombace (1989) and Fourrier & Barral (2009)
Leucate-Le Barcarès	2004	60 pipes, 36 chaotic heaps with pipes, 72 Dalots, Dalots and concrete platforms	2,200	15–30	Anti-trawling Maintain artisanal fishing	Lenfant et al. (2007), Fourrier & Barral (2009) and Koeck et al. (2011)
Canet-en-Roussillon	1985	8 Bonnas, 6 heaps of 14 Comins	2,138	17–30	Anti-trawling Maintain artisanal fishing	Bombace (1989) and Fourrier & Barral (2009)
Saint-Cyprien	1985	9 Bonnas, 7 heaps of 14 Comins	2,420	17–30	Anti-trawling Maintain artisanal fishing	Bombace (1989) and Fourrier & Barral (2009)
Total LR			37 575			
Atlantic, english channel coasts						
Etretat	2008	169 Cubic reefs, Block of 53 m^3	456	–	Maintain artisanal fishing Experimental test	Data unpublished

Table 1 continued

Deployment area	Year of deployment	Description of artificial reefs	Dumped volumes (m^3)	Dpth of deployment (m)	Objectives	References
Concarneau	1970/73	Rocky blocks, old tires	≈200	–	Experimental test	Bombace (1989)
Croisic	2003	Chaotic and organized heaps of cubic reefs of 5 m^3, 1 module of 156 m^3	–	30	Experimental test	InVivo (2006)
Yeu Island	2003	Chaotic and organized heaps of cubic reefs of 5 m^3, 1 module of 156 m^3	–	20 and 47	Experimental test	InVivo (2006)
Arcachon (Pilat)	1972	26 Car wrecks	–	12–18	Experimental test	Barnabé et al. (2000)
Mimizan	1990	Old tires	–	25	Maintain artisanal fishing	Bombace (1989)
	2000/06	Bonna pipes	–	–		Data unpublished
Messanges/ Moliets	2003	3 Heaps of 200 Bonnas	600	20	Maintain artisanal fishing	Dalias & Scourzic (2006)
	2010	3 Typi	44	18–20		Fourneau G/ALR (pers. comm.)
Boucau/ Soustons	2001/02	7 Heaps of 5 Bonna pipes	800	18–20	Maintain artisanal fishing	Dalias & Scourzic (2006) and Sanchez & Scalabrin (2008)
	2010	3 Typi	44	18–20		Data unpublished
Capbreton	1999	800 Bonna pipes	2,400	18–20	Maintain artisanal fishing	Dalias & Scourzic (2006)
	2008	125 Bonna pipes	375	18–20		Fourneau G/ALR (pers. comm.)
	2010	3 Typi	44	18–20		Fourneau G/ALR (pers. comm.)
Total Atlantic, english channel coasts			≈4,963			
Corsica						
Bastia	2008	Box in concrete containing breeze blocks	250	17–19	Maintain artisanal fishing Experimental test	Pelaprat et al. (2010)
Total corsica			250			
Reunion Island						
Saint Paul	1995, 2000	3 Heaps of plastic containers and tires with vertically floating	18	15	Maintain artisanal fishing	Tessier et al. (2005)
Saint-Leu	1999	Wreckship	–	–	Development of diving	Arvam (2003)

Table 1 continued

Deployment area	Year of deployment	Description of artificial reefs	Dumped volumes (m^3)	Dpth of deployment (m)	Objectives	References
La possession	2002	3 Heaps of rocky blocks, 18 piles of perforated plates and 2 concrete plates with rope streamers	1,048	20–30	Maintain artisanal fishing	Tessier (2005)
	2008	2 Hexapods of electricity poles, 2 heaps of 2 piled voussoirs , 2 floating ropes	60	15–25	Development recreational activites	Pareto & Arvam (2010)
Saint Leu, Le Port	2008	1 Hexapod of electricity poles and floating ropes	8	15–25	Maintain artisanal fishing Development recreational activites	Pareto & Arvam (2010)
Martinique						
Case pilote, ilet ramier, bay of robert, trinite	2003	Rocky blocks	–	–	Maintain artisanal fishing	Data unpubilshed
Total DOM-TOM			≈1,134			
Total France			≈93,982			

If a site already exists and has over time been adding dates RAs then dips appear at this site. Some sites have been several deployments in order to make denser them and to strengthen their performance according to their objectives

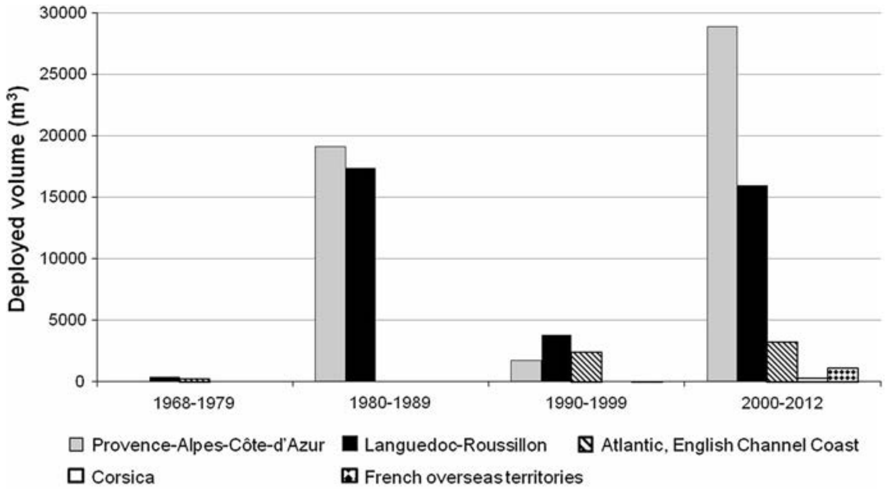


Fig. 3 Volume of artificial reefs built in France as a function of decade and region

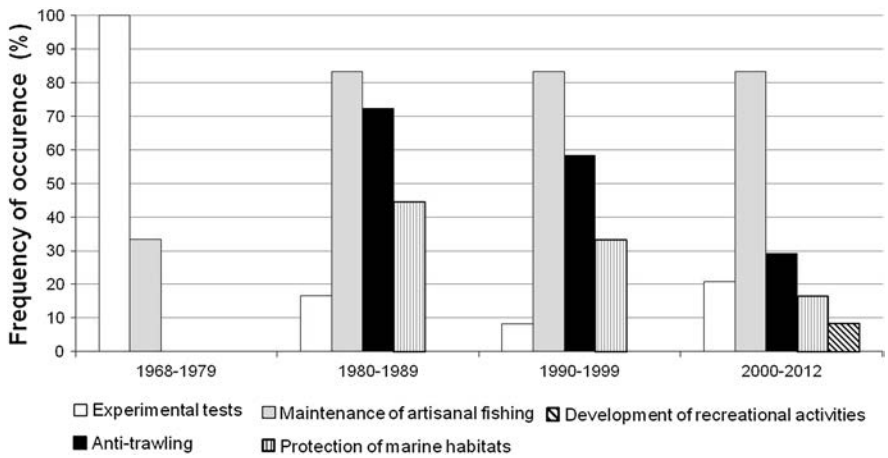


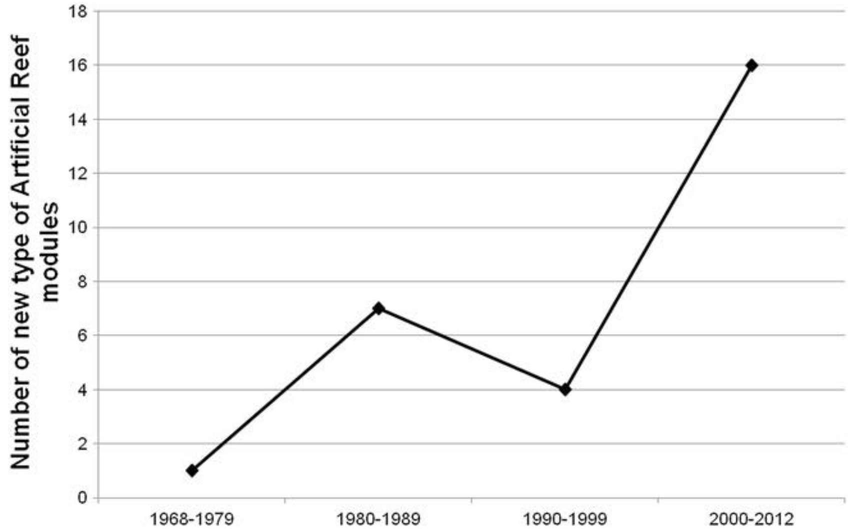
Fig. 4 Frequency of occurrence of the principal objectives of French artificial reefs according to decade

Other objectives achieved (Table 1), sometimes in concert at one site, include protection of habitat from illegal trawling within three nautical miles of shore, restoration of ecosystems, biodiversity enhancement, research, establishment of recreational activities including fishing and diving, and integrated management of coastal ecosystems, specifically in concert with Marine Protected Areas (MPAs). SCUBA diving on ARs is reported by Pinault (2013). One objective of the AR of Reunion Island is to open them to new regulated uses such as SCUBA diving to sustain their cost effectiveness (Pareto & Arvam, 2010). A potential use is enhancement of habitats created by foundations of offshore wind farm structures (Lacroix & Pioch, 2011). The chronology of major objectives of ARs is depicted in Fig. 4.

The first ARs in France were used in small scale experiments to understand benthic colonization (Barnabé et al., 2000), an objective no longer emphasized. Research on the design of reef modules began in 1988. Several experiments have been conducted to test the effects of increasing habitat complexity on the ecological response of individual species and assemblages (Charbonnel et al., 2002; Bodilis & Dombrowski, 2008; Bodilis et al., 2011).

Since 2000, bivalve shellfish culture on ARs has not been reported in the literature. The use of ARs as anti-trawling devices has greatly decreased after 2000 despite their success in protecting sensitive habitats such as seagrass (*Posidonia*) meadows as reported by Barnabé et al. (2000) and Charbonnel & Bachet (2010). These ARs were deployed to reduce illegal

Fig. 5 Evolution of the number of new types of artificial reef modules made in concrete in France



trawling in coastal waters. At present, most of the collectivities and stakeholders consider that immersion of anti-trawling ARs is difficult to sustain by communities; better law enforcement is sought (Direction inter-régionale de la mer, 2012).

During the next decade (i.e., post 2015), the volume of reefs will likely to increase in different regions, although some planning information is confidential. Some AR projects have recently been launched on the west coast of Oléron Island (Charente-Maritime, Atlantic coast) with a first phase of experimentation about module design and a final objective to improve species richness of fishes of commercial interest (CREAA, 2011). Also, creation of new ARs in the overseas departments and territories includes Reunion (Indian Ocean), Martinique, and Guadeloupe (Western-Central Atlantic) islands. Their objective seeks compensatory measures for the degradation of coral reefs caused by anthropogenic pressures (Pinault, 2013).

Artificial reefs design and materials

AR deployments since about 2000 include both an increase in the number of designs used based on field research and also the use of concrete as the principal construction material. With increased emphasis on stability and longevity of reef structure, the use of waste products such as automobile bodies and old tires has been discontinued since 1980. In place of the so-called materials of opportunity that might have little justification biologically, 16 new AR designs have been used (Fig. 5; Table 2), typically seeking to meet objectives aligned with life history requirements of given species. Barnabé et al. (2000) identified 12 designs used prior to 2000, including materials of opportunity.

Much of the design process has been driven by biologists concerned with reef module attributes such as shape, void space, and interior space as they influence invertebrates and especially fishes. Historically, AR modules mainly were designed by construction companies (e.g., The Bonna AR; Table 2), but presently the effort is led by scientists employed by city governments (e.g., Marseille), non-governmental organizations [e.g., Cépralmar, Association Lande Récif (ARL), Centre Régional d'Expérimentation et d'Application Aquacole (CREAA)], and private companies (e.g., BRL, Hydro M, Architeuthis, EgisEau, Seaboost, P2A Développement). The ecological consequences of various reef designs are reviewed below.

The scheme of deployment of AR modules also has changed since the first deployments. Using an urbanization concept, AR modules are now frequently disposed in "village" with an arrangement thought between modules and "villages" to allow connectivity between themselves and natural areas (Charbonnel et al., 2011; Koeck et al., 2011). Currently, "villages" t and cluster of several sets correspond to the terminology of reef "sets" and "groups" originated in Japan (Grove & Sonu, 1983; Bohnsack &

Table 2 Characteristics of different modules used in deployments of artificial reefs in France. (modules are organized alphabetically)

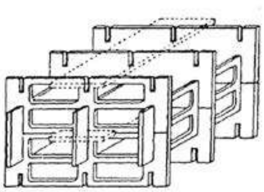
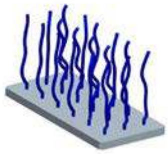
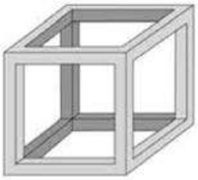
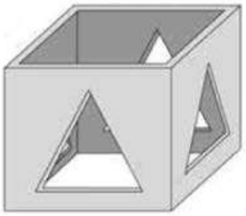
Illustration	Name- Measurements and illustration references	Illustration	Name- Measurements and illustration references
	Alveolar Pyramidal Height: 2.5m Length: 2.5/1.45m Width: 2.9/1.85m (Charbonnel & Bachet 2010)		Block of 53 m^3 © Chambre de Commerce et de l'Industire de Fecamp
	Bonna Height : 4.4m Length: 6m Width: 6m (Duval-Mellon 1987)		Bonna pipe Diameter : 1.20m Length: 1m © G. Fourneau
	Breeze block module Height : ≈2m Length: ≈2m Width: ≈2m (Barnabé et al. 2000)		Maze Height: 2.2m Length: 4m Width: 2m (Charbonnel *et al.* 2011) © E. Charbonnel
	Comin Height : 2.30m Width: 2.30m © M. Foulquié		Concrete plate with rope streamers © P2A Développement
	Cubic reef of 1 m^3 Height: 1m Length: 1m Width: 1m (Charbonnel & Serre 1999)		Cubic reef of 1.4 m^3 Height: 1m Length: 1.2m Width: 1.2m (Charbonnel & Serre 1999)

Table 2 continued

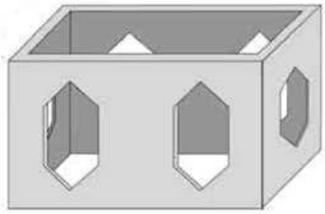
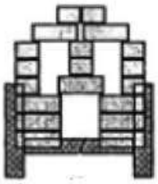
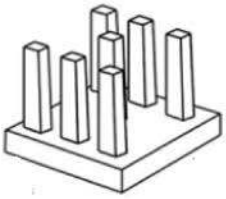
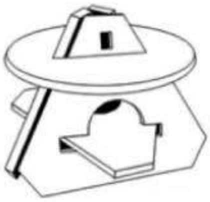
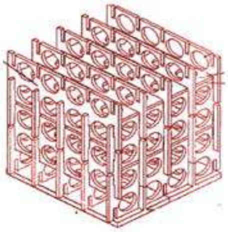
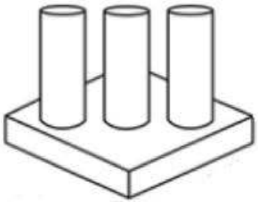
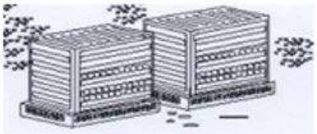
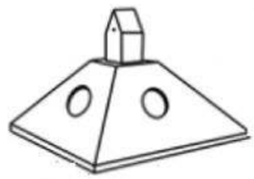
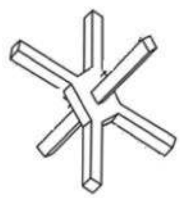
	Cubic reef of 2 m^3 Height: 1.25m Length: 1.7m Width: 0.9m (Charbonnel & Serre 1999)		Cubic reef of 5 m^3 Height: 1.32m Length: 2.10m Width: 1.82m © In Vivo
	Dalot Height : 2m Length: 2m Width: 2m © Cépralmar		Experimental module Height: 50cm Length: 60cm Width: 60cm (Charbonnel & Bachet 2010)
	Fakir electric piles Height: 1.6m Length: 2.5m Width: 2.5m (Charbonnel & Bachet 2010)		Floating ropes Height: 7m Length: 6m Width: 6m (Charbonnel *et al.* 2011) © Ville de Marseille
	Heaps with telegraph poles © Cépralmar		Hexapod of electicity poles © PARETO
	Kheops Height: 2.4m (Charbonnel & Bachet 2010)		Module of 156 m^3 Height: 5.89m Length: 5.15m Width: 5.15m © In Vivo
	Négri column Height: 1.6m Length: 2.5m Width: 2.5m (Charbonnel & Bachet 2010)		Pile of perforated domes © P2A Développement

Table 2 continued

	Pile of perforated steel plates ©P2A Développement		Pipe Diameter : 1.9m Length: 2.5m © M. Foulquié
	Sabla Height : 1.20m Length: 1.20m Width: 1.20m © M. Foulquié		Sea Rock Height: 1.3m Length: 2m Width: 2m (Charbonnel & Bachet 2010)
	Spiral staircases © Cépralmar		Steel basket Height : 3.85m Length: 5m Width: 3m © M. Foulquié
	Thalamé Diameter : 3.3m Length: 1.07m © A. Meinesz		Tripod Height of 1 spine: 4m (Charbonnel & Bachet 2010)
	Typi Height: 2.6m Width at bottom: 4,6m © G. Fourneau		Voussoir © PARETO

Sutherland, 1985) and more recently used in other nations, such as Portugal (Santos et al. 2011, Fig. 14.2). Biologically, such dispersal of material promotes the movement of some organisms between two distant favorable habitats creating ecological corridors, which contribute to maintenance and stability of populations (Bohnsack & Sutherland, 1985; Charbonnel et al., 2010). The use of different modules and their placement in "village" and cluster of "villages" named "hamlet" increase the global complexity of this artificial habitat to approach that of natural habitats [Fig. 6; see also (Cheminée et al., 2014), for a review of these seascape approaches].

Funding for artificial reefs

Funding for ARs continues in France. It was increased in the 1990s by sponsors at the community,

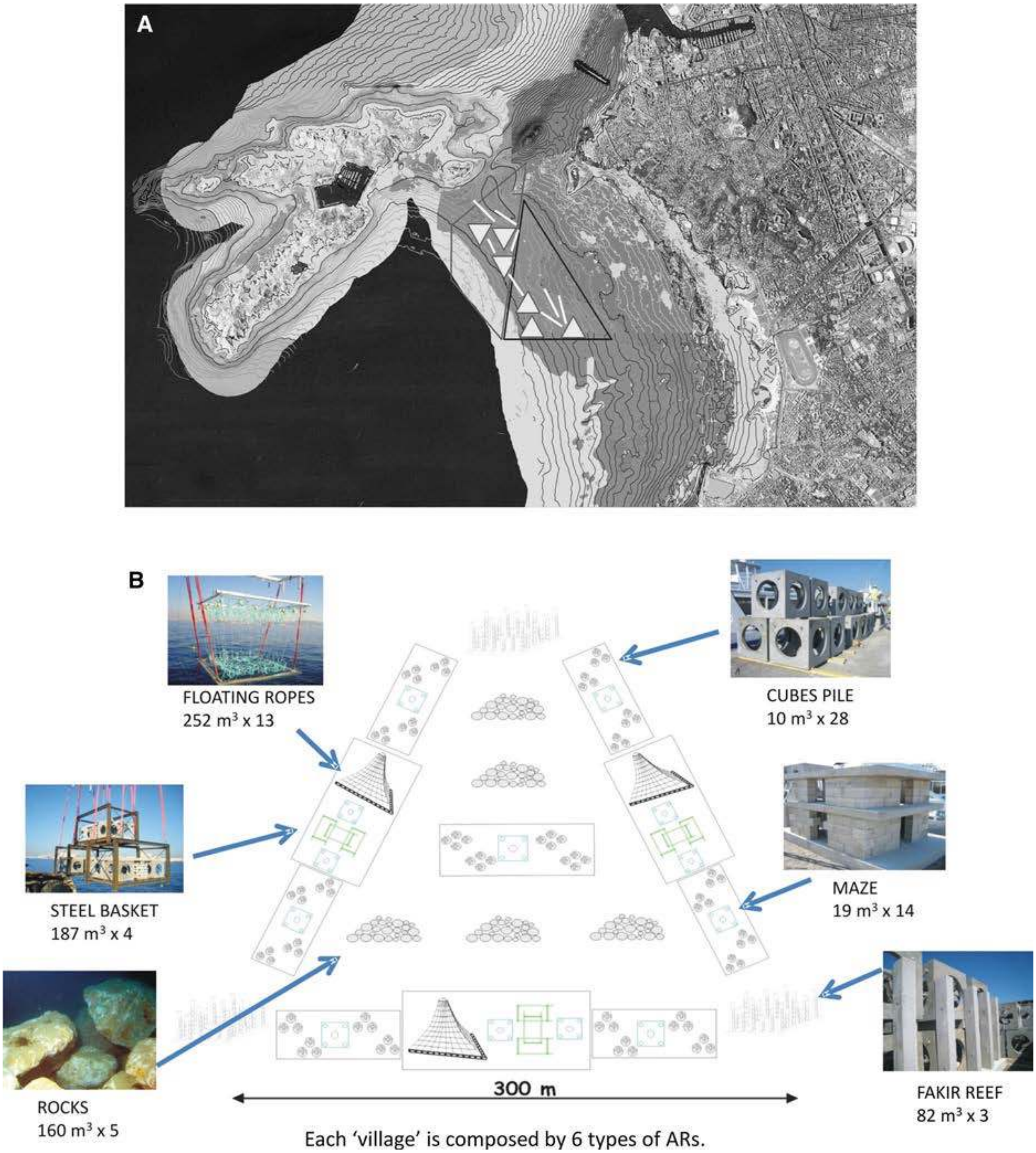


Fig. 6 **A** France: Marseille Prado artificial reefs, the largest reef deployed in Mediterranean in 2007–2008; composed of six villages (*triangle* on the map) inked by 8 connections (*bold lines* in *white* on the map) © Ville de Marseille **B** Each village has a *triangular shape* and constituted with 6 types of ARs (below) (from Charbonnel et al., 2011) ©BRL and Ville de Marseille

department, and regional levels (Barnabé et al., 2000). Since about 2000, the France and the European Union have been involved also through the *Financial Instrument for Fisheries Guidance* (FIFG) and more recently through the *European Fisheries Fund* (EFF). The European Economic Union is now frequently the main sponsor, contributing up to 50 % of the cost of projects (Fig. 7). Typical sponsors of ARs include, in

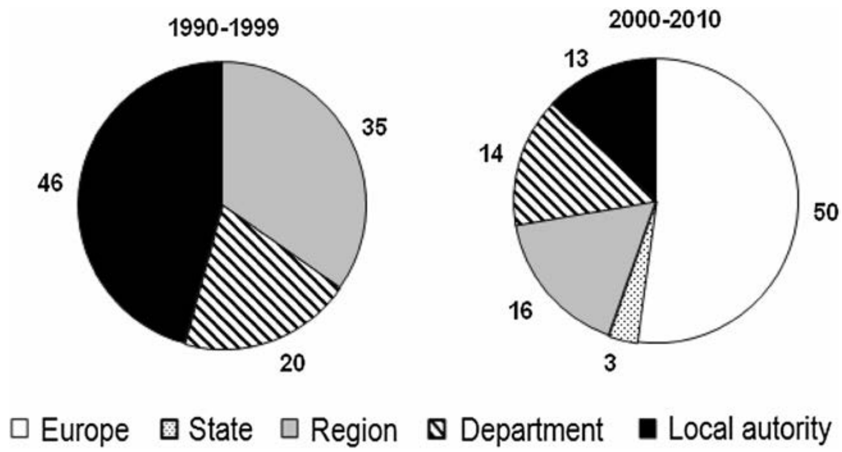


Fig. 7 Percentage of participation for a French project of artificial reefs according to sources of funding and decade

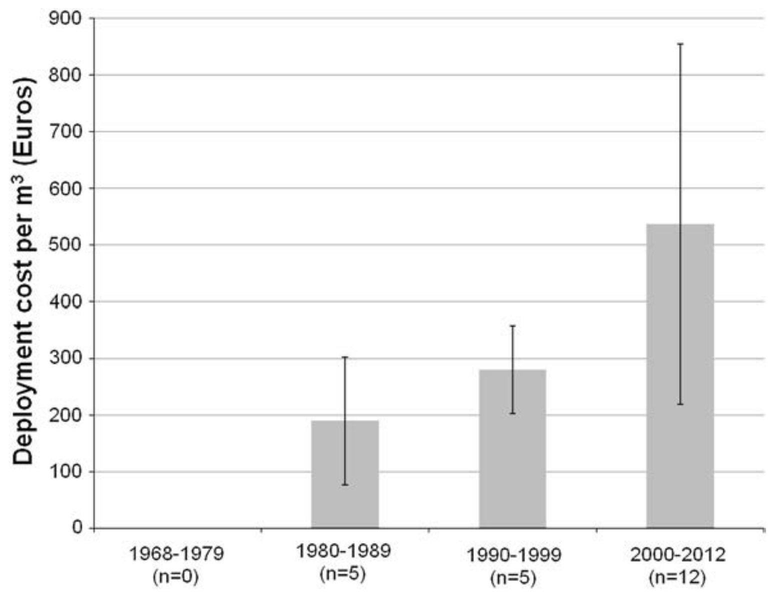


Fig. 8 Mean deployment cost per m^3 of French artificial reefs according the decade with standard error; n: number of immersion project considered to calculate the mean cost (Euros adjusted for inflation over time with 2010 used like the base-year)

the same proportion of participation, the Local authorities, the Department, and the Region (local government) concerned with the project.

Although information on costs of AR development and construction is uneven among projects and is difficult to obtain, some representative data are provided here. For example, at Côte Bleue Marine Park over 25 years, a total of 480,000 Euros were invested in ARs at five sites for a global amount of reef material with a volume of 4,884 m^3 (98 €/m^3) (Charbonnel & Bachet, 2010). The largest object of funds has been at Marseille with a total deployment cost of 4,270,000 Euros for a gross volume of 27,300 m^3 (156 €/m^3). The cost of ARs per m^3 has increased every decade and after 2000 the mean deployment cost per m^3 was 500 Euros (Fig. 8).

To our knowledge, however, no comprehensive socioeconomic research concerning impact, cost-benefit and cost-effectiveness analyses (i.e., principal methods as indicated by Milon et al. (2000)) has been conducted for ARs in France. This contrasts with assessments such as those done for the AR complex in the Algarve of Portugal (Santos et al., 2011) that document sustainable contribution of artisanal fishing to the local economy.

Table 3 French artificial reefs (ARs) with regulation and surveillance deployed in France

Deployment area	Year of deployment	Type of regulation	Jurisdiction enforce	Existence of surveillance
Languedoc-Roussillon				
Agde	1985	Prohibition anchoring, dredging, diving and spear fishing	Prefectorial decree	No
Provence-Alpes-Côte d'Azure (PACA)				
Golfe Juan	1989/1991/93/96	Prohibition anchoring, dredging, diving and all types of fishing	Prefectorial decree	No
Beaulieu-sur-Mer	1980/83/85/87/ 1990/91	Prohibition anchoring, dredging, diving and all types of fishing	Prefectorial decree	No
Roquebrune	1980/83/85/87/ 1990	Prohibition anchoring, dredging, diving and all types of fishing	Prefectorial decree	No
Côte Bleue Marine Park	1983/85/87/89/ 1996/97/2000/ 2004	Prohibition of all activity within the 2 integral reserves, Open access outside the reserves	Ministerial and Prefectorial decree	Yes
Port-Cros	1985/1997	Prohibition anchoring and all extractive activity, Prohibition of diving	Management plan of the park	Yes
La Ciotat	1986	Prohibition of all activity	Prefectorial decree, not in force since 1994	No
Beauduc	1989	Prohibition of artisanal fishing	Management plan of the park	No
Marseille	2007/08	Prohibition anchoring, diving Prohibition of all fishing in a part of ARs and on other regulated	Management plan of ARs	No
Cagnes-sur-Mer	2009	Prohibition anchoring and diving	Information no obtained	No
Atlantic, english channel coasts				
Mimizan	1990/2000/06	Prohibition anchoring, diving and all types of fishing	Prefectorial decree	No
Capbreton	1999/2008/10	Prohibition anchoring, diving and all types of fishing	Prefectorial decree	No
Boucau/soustons	2001/02/2010	Prohibition anchoring, diving and all types of fishing	Prefectorial decree	No
Messanges/Moliets	2003/2010	Prohibition anchoring, diving and all types of fishing	Prefectorial decree	No

The ARs not mentioned in this table lacked regulation

Management of artificial reefs

Regulations applied to ARs before and after 2000 generally are unchanged. Before 2000, half of the ARs in France were regulated. All these ARs have a status of "fishing reserve", whereby fishing, anchoring, dredging, and diving are automatically prohibited by a prefectorial decree from the juridical authority (Table 3). Regulations have been ineffective due to the lack of staff within the different authorities in charge of the sea (Affaires Maritimes, fishing councils, or even local fishing committees). Reefs that have received regulation associated with enforcement are those within Marine Protected Areas (MPAs), with dedicated rangers. This is the case at Côte Bleue Marine Park (Charbonnel & Bachet, 2010) and Port-Cros National Park (Charbonnel et al., 2001a).

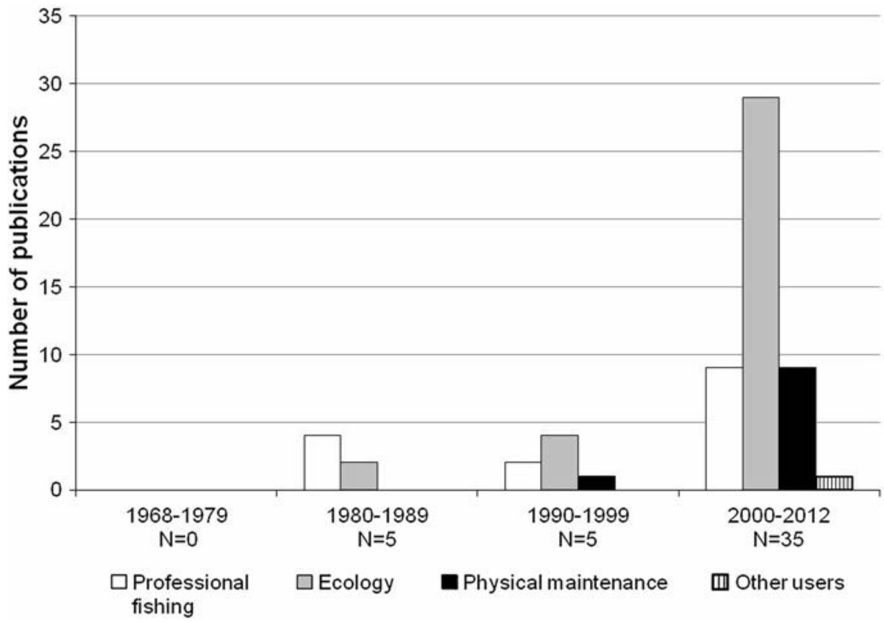


Fig. 9 Number of publications about French artificial reefs according the decades and the studied component; N indicates the total number of publication; A publication could be deal with several component

Assessment of the ecological monitoring of artificial reefs

Of 35 research publications concerning artificial reefs in France since 2000, 30 pertain to ecological aspects. Fisheries associated with publications, physical stability of the structures, and stakeholder perceptions and attitudes receive less attention (Fig. 9). One publication analyzed the potential toxic chemical effects of old tires that comprise artificial reefs in Golfe-Juan, involving the transplantation of marine mussels, *Mytilus galloprovincialis*, to sites located above tires blocks or reference site (Risso de Faverney et al., 2010). The objectives of the ARs are given in Table 1.

Abundance and diversity of animal species, especially fishes, are the ecological attributes most commonly assessed at the artificial reefs of France, and these were typically assessed using standard methods of underwater visual census by divers (Bortone et al., 2000). These studies also provide various observations for the ecology of at least selected species, and make limited assessment of interactions of the ARs with the larger ecosystem. Sessile flora and fauna are rarely studied. Below we summarize ecological research findings concerning 10 of the 33 AR sites in France (Table 1), reported subsequent to the review of 17 publications from 1984 to 1998 by Barnabé et al. (2000). We have chosen to focus our assessment on Mediterranean ARs because they present a substantial level of monitoring compared to Atlantic and oversea territories.

Richness and abundance of fish fauna

Studies of the presence of fishes at ARs emphasized two attributes of the structures, namely reef module design and age, which were described in 70.5 % of the post-2000 (i.e., "recent") publications reviewed. Despite the proliferation of AR-related publications in that period, only one (Koeck et al., 2011) was peer-reviewed. This is consistent with the trend noted by Barnabé et al. (2000) for the preceding three decades. The absence of external peer review reflects the context for much reporting of recent French AR research, which has been sponsored by local authorities responsible for reef deployment using EEU funding and thus fulfilling its mandates for monitoring. The practice of these authorities has been to work with private companies on projects with limited scopes of work and restricted objectives, methods and analyses, and with findings presented in contract reports of limited circulation. Only half of recent monitoring studies used statistical tests to compare fish assemblage species richness and density between modules and years (Koeck et al., 2011; Blouet et al., 2012; Dalias et al., 2012). Furthermore, the used statistical tests (e.g., Kruskal–Wallis test, Mann–Whitney test) were not the most appropriated regarding the sampling design (Blouet et al., 2012; Dalias et al., 2012). Indeed, Claudet (2006) recommended the use of permutational tests. In contrast with these limitations, managers of Languedoc-Roussillon ARs sought academic researchers to organize large-scale statistical analyses based on their experience and expertise in the subject.

Recent investigations of ARs were either short term (<5 years with an interval of 1 year), or long term (>10 years with an interval of 10 years). Short-term investigations were typical of the littoral coast of Languedoc-Roussillon (6 of 7 studies), while the latter were exclusive to Provence-Alpes-Côte d'Azure (PACA). This difference is due partly to the more recent period of AR deployment in Languedoc-Roussillon (Table 1; Fig. 2); the obligatory survey required by EEU funding, but with monitoring limited to 5 years; and different management structures (local administration at the city scale, versus marine protected area managers). Thus, when ARs are incorporated into marine protected areas, they can be surveyed for longer than 5 years because their monitoring can be included in the long-term management plan of the area.

Recent short-term studies reported that in the 1 month after AR deployment, fishes had colonized the structures (Le Diréach et al., 2011a; Blouet et al., 2012), although initial species composition was not given. The studies showed that the families Labridae (*Symphodius* spp.), Sparidae (*Diplodus sargus*) and to a lesser degree Scorpaenidae (*Scorpaena notata*) dominated, by weight, the assemblages. Similarity of the AR ichthyofauna to that associated with natural rocky (NR) habitat has led to the conclusion that ARs mimic NRs (Koeck et al., 2011; Le Diréach et al., 2011a; Dalias et al., 2012). These studies found differences in diversity and abundance of fishes at certain AR modules. For example, steel basket or chaotic heaps (Table 2) always supported higher mean species richness (roughly 1.3–1.7 times greater) than other modules (Lenfant et al., 2009; Koeck et al., 2011; Le Diréach et al., 2011a; Blouet et al., 2012). These modules also often had greater abundance of fishes (Lenfant et al., 2009; Koeck et al., 2011; Le Diréach et al., 2011a; Dalias et al., 2012). One explanation offered for these differences is the variation of AR architectural complexity (Lenfant et al., 2009; Koeck et al., 2011; Le Diréach et al., 2011a; Dalias et al., 2012). This conclusion is a basis for experiments with AR modules of varied physical complexity (see "Effect of habitat complexity on fish fauna" section). Other short-term studies also highlighted the increase of mean species richness over time (e.g., 2010: 3.5 species and 2011: 6 species (Lenfant et al., 2009)), but not of abundance (CREOCEAN, 2008; Lenfant et al., 2009; Koeck et al., 2011; Le Diréach et al., 2011a; Blouet et al., 2012; Dalias et al., 2012). Not all short-term studies were conclusive concerning trends of increase or decrease in fish abundance at ARs (Lenfant et al., 2009; Le Diréach et al., 2011a; Blouet et al., 2012; Dalias et al., 2012). It is possible that the year of deployment was not the main factor of fluctuation. It is possible that some biological factors (e.g., recruitment, variation of food) induce these variations of abundances. However, no French study has investigated this possibility. Species richness studies were similarly limited as to conclusiveness, whereby levels could be either similar between ARs and NRs (Le Diréach et al., 2011a), or inferior on ARs versus NRs (Blouet et al., 2012), or else greater on ARs versus NRs (Dalias et al., 2012). The role of environmental conditions should be considered in explanations of trends of fish abundance and diversity, but information about parameters such as turbidity, dissolved organic matter, current, and chlorophyll *a* has not been gathered in the AR studies.

Long-term AR fish surveys showed that Labridae, Sparidae, and Scorpaenidae dominated the assemblages (Bodilis & Dombrowski, 2008; Bodilis et al., 2011). Even more than 10 years after deployment, species richness continued to increase, with the appearance of *Diplodus puntazzo*, *Gobius geniporus*, *Gobius paganellus*, *Scorpaena scrofa,* or *Epinephelus marginatus,* for example (Charbonnel et al., 2001b; Charbonnel & Bachet, 2010; Le Diréach et al., 2011b, Bodilis et al., 2011). At the Côte Bleue Marine Park AR site, mean species richness was multiplied by a factor of 4 between 1995 (10 years after deployment) and 2004 (19 years after deployment) (Charbonnel & Bachet, 2010). Colonization of new benthic habitats is a long process (Kareng & kolding, 1995; Whitmarsh et al., 2008; Lenfant et al., 2009). Longer term AR studies described the same trends as in the shorter studies (Charbonnel et al., 2001b; Bodilis & Dombrowski, 2008; Charbonnel & Bachet, 2010; Bodilis et al., 2011; Le Diréach et al., 2011b). High variability of fish density between years was always observed (Charbonnel et al., 2001b; Bodilis & Dombrowski, 2008); the time of AR deployment did not seem to reduce these fluctuations. Typically, AR survey reports did not consider the relation of fish abundance to reef unit surface or volume.

Compared to ARs, fish species richness and abundance were lower at nearby natural areas (e.g., Lenfant et al., 2009; Dalias et al., 2012). We hypothesize that the higher parameters for these variables at ARs were induced: (i) by the presence of favorable hard substratum instead a great sand area (attraction effect) and (ii) by the limitated use of fish nets on ARs (protection effect) (Lenfant et al., 2009; Koeck et al., 2011; Dalias et al., 2012). Evidence for production of new biomass, meanwhile, may be indicated by the presence of juveniles on ARs during the summer, which suggests that the ARs could be a site for reproductive activity (Lenfant et al., 2009). Futhermore, a recent work on isotope realized by Cresson et al. (2014) on Prado ARs, but not considered in this part of paper because published after 2012, go to confirm the production of a new biomass by ARs.

Effect of habitat complexity on fish fauna

Since 2000, only one study addressed the effect of the complexity of AR, conducted in Golfe-Juan using a specific reef type, a Bonna (Charbonnel et al., 2002). An empty Bonna (158 m^3) was modified by the addition of 37 m^3 of building materials such as bricks and pipes, providing 4,110 cavities and a seven-fold increase in surface area of the unit (Table 2). A comparison of empty and “complex” Bonna reefs allowed a test of the effects of increasing habitat structural complexity upon fish abundance and diversity. Charbonnel & Serre (1999) provided additional information. Monitoring by divers in 1987–1989 and 1997–1998 detected twice the number of species. A total of 17 families and 40 fish species were observed. Eight species were of commercial value. Six species were only observed on the complex Bonna (*Dentex dentex*, *Diplodus puntazzo*, *Epinephelus marginatus*, *Sciaena umbra*, *Conger conger*, *Phycis phycis*) and not captured. This study showed significantly higher mean density and biomass of fishes at the experimental artificial reef module than at the unmodified (i.e., less complex) control reef. The “ecological effectiveness” of the complex Bonna was enhanced due to the influence of increased structural complexity upon both food availability and behavioral aspects (Charbonnel et al., 2002). The structure of the fish assemblage changed, with the appearance of species that could be considered permanent and frequent. These species included fishes with a wide home range, such as *Diplodus sargus* and *D. vulgaris*, cryptic, sheltered species including *Scorpaena* spp. and *Conger conger*, and benthic families including Blenniidae and Gobiidae. Again, Labridae and Sparidae were the most dominant groups. The domination of fish assemblages by permanent and frequent species could suggest a higher temporal stability of the species (Charbonnel et al., 2002). In 2008, domination by permanent and frequent species was confirmed (Bodilis & Dombrowski, 2008; Bodilis et al., 2011)

Sessile flora and fauna

The sessile flora and fauna of ARs in France have been addressed in only three publications (CREOCEAN, 2003, 2008; Le Diréach et al., 2011a). The Prado AR system of Marseille was surveyed in 2009–2010 to test for patterns of colonization of the sessile species according to the type of modules (heaps of cubic reefs, mazes, steel baskets and fakir electric piles; Table 2) (Le Diréach et al., 2011a). The species were determined on the basis of photo quadrats and according to five taxa (algae, bryozoans, sponges, ascidians, turf and unidentified) (Le Diréach et al., 2011a). In general, the turf (algae less than 2-cm high) was dominant in 2009 but decreased in 2010. Ascidians were more abundant on heaps of cubic reefs and steel baskets, sponges on mazes and on fakir electric piles the ascidians and sponges were in the same proportion.

At Aigues-Mortes, photo quadrats were also carried out during the three years of monitoring (CREOCEAN, 2003). The colonization of the module increased through time, with a succession of species. Suspensivorous species dominated the sessile fauna population with few detrivorous and deposivorous taxa represented (CREOCEAN, 2003). At Gruissan, there were 5 years of monitoring of module colonization by benthic fauna followed the methods used at Aigues-Mortes (CREOCEAN, 2008). No clear trend (increase or decrease) was highlighted in the number of species settling on ARs (CREOCEAN, 2008, p 59). However, it was assumed that colonization success on the AR is higher in shallow water and for ARs with a complex structure (CREOCEAN, 2008). Due to few studies dealing with flora and fauna colonization, it is impossible to draw general conclusions. However, this compartment must be studied because of the need for information to analyze food webs of AR systems.

Synthesis and conclusions of ecological aspects

Our review of literature about ecological research of ARs indicates that the majority of studies emphasized monitoring, usually over a short term and few of these conducted experimental studies. This reflects policies linked to the financial model of ARs, whereby the European Economic Union imposes an "obligatory monitoring" effort for 5 years, post-deployment. As monitoring usually has been conducted by private companies, there are few papers published in peer-reviewed journals (only four out of 21 papers). Instead, these contract-fulfillment reports were popularized to be understood by the funding authority and they have not been written in scientific language. Our conclusion is that research subsequent to the Barnabé et al. (2000) review added little to our understanding as to how ARs function. In other words, the most recent studies continued to apply the earlier methods of observation, and dealt with the same variables studied earlier, although these studies did alter their focus to species of commercial value. Evidence that this trend may change in the next decade is seen two graduate theses that deal with fundamental ecological aspects of ARs, i.e., their roles in the life history of *Diplodus vulgaris* (Koeck, 2012) and in biomass production and food chains (Cresson, 2013). For the last decade, if we synthesize the scientific advancement and contribution to knowledge about the functioning of AR, the main advances have been (i) highlighting the time necessary for the AR system to attain maturity, and (ii) some quantification of the important role of structural complexity of the artificial habitat to sustain an abundant fish assemblage.

Applications of artificial reefs in coastal management and perceptions by users

Worldwide, the main objective of ARs is to be a management option, albeit modest, to sustain long-term fisheries, sometimes in the face of chronic declines in marine fisheries and deterioration of ecosystems (Seaman et al., 2011). French researchers have evaluated ARs in the context of management applications to restore, conserve, and even enhance fisheries and habitats, in 16 projects reported after the review by Barnabé et al. (2000), using two different approaches. The more common is the halieutic approach. The assessment of these studies constitutes the first part of this section. The second point of view concerns Social and Human Sciences and involves perception of artificial reefs by fishermen.

Effectiveness to maintain artisanal fishing

The main expectation of ARs is that fishing yields are similar or higher around them than at areas without ARs. However, the variable 'presence of individuals' does not confirm, by itself alone, a positive effect of ARs for artisanal fishing. For example, it is possible that the catch ratio is lesser at ARs than at a natural area, the individuals present on ARs have a size under the commercial limit, or that the species are less easily caught at ARs than at natural reefs. The prime interest for the fishermen is that they catch more fish after rather than before the deployment of ARs. When fishery-related aspects of ARs in France have been studied, it usually has been as part of (broader) ecological monitoring, on a temporal scale. However, analyses of fishery yields generally lack both clear BACI (Before AR deployment-After AR deployment-Control-Impact) protocols and also reference to factors such as module configuration, complexity, and depth. French studies with a BACI approach have been few 3 publications of the 11 investigated publications (Duval-Mellon, 1987; Jouvenel & Faure, 2005; Blouet et al., 2011). Furthermore, the results of BACI studies were not evaluated because they have not been published in a peer-reviewed journal. The studies presenting BACI protocols reflect the problem of time lag between the availability of funding (after the deployment) and the deployment itself.

Experimental fishing is the most common sampling technique used to test if fishing yield increased after AR deployment, or at AR rather than at natural reefs. Both gill nets and trammel nets are commonly used (50 % each), although a previous study employed trawls (Duval-Mellon, 1987), and another study used longlines (Jouvenel & Roche, 2011). Species richness was usually studied, and density and biomass catch-per-unit-effort less frequently. The four studies showed that there was no significant difference between ARs and natural reefs sites for species richness (CREOCEAN, 2003; Lenfant et al., 2009; Jouvenel & Roche, 2011; Dalias et al., 2012). However, the results for density and biomass were contradictory among the reviewed papers. There was no clear tendency for evolution over time. Half of the reviewed papers indicated a decrease in species richness and the other half indicated no change in species richness after the deployment.

Of two recent studies that employed experimental fishing using a BACI protocol (Jouvenel & Roche, 2011; Blouet et al., 2012), only Blouet et al. (2012) indicated an increase (two times) of biomass of fish between before (8 $kg/m^2/h$) and 1 year after (16 $kg/m^2/h$) AR deployment. But, these variables seem to be stable for the years after the deployment (Blouet et al., 2012).

The other method used to analyze the AR effect on artisanal fisheries is to survey landings. The main bias linked to this assessment method is the inaccessibility of discards. In the Languedoc-Roussillon region, a survey of fisheries landings began in 2007 (Lenfant et al., 2009). It followed a large study area along 60 km of coastal zone, including the AR location. Its large space permitted evaluation of natural habitat independent of AR influence. The authors found that ARs sustained catches at levels similar to those at natural habitat, despite the fact that harvests decreased in neighboring areas (Lenfant et al., 2009). In this case, fishermen used less fuel due to shorter travel distances, although elsewhere they prefer to travel long distances and accept increased gas and oil consumption to catch higher fish biomass near AR (A. Tessier, pers. obs.).

One notably useful study of long-term fishing and ecosystem management is based on the ARs of the Côte Bleue Marine Park (Fig. 2), where biological "production reefs" and habitat "protection reefs" were deployed. These ARs have contributed to preservation of traditional small-scale fisheries, involving about 60 fishermen (Charbonnel & Bachet, 2010). These authors draw on a 25-year database that indicates effectiveness in drastically reducing illegal trawling by placement of ARs (Charbonnel & Bachet 2010, Fig. 3). Biological results include conservation of seagrass meadows and their nursery function, and the resulting survival of juvenile fishes no longer captured due to the use of selective gear for adults (e.g., gillnets and trammel nets). Different AR structures intended to produce fish biomass have been determined to be comparable or even better than natural rocky habitats, particularly as they address habitat limitation by providing shelter that is highly heterogeneous. Long-term trends showing increase of species and biomass assemblages as a function of AR maturity were reported by Jouvenel & Bernard (2006). Charbonnel & Bachet (2010) concluded that the ARs function as MPAs by having "reserve effects" that increase overall biodiversity and abundance of target fishery species, and also restore the presence of larger individuals that spawn and have a refuge effect.

It is difficult to make conclusions about the ARs effectiveness due to the lack of homogeneity among the protocols and the treatment of data between the studies. The non-standardization of protocols between AR surveys becomes problematic when comparing AR sites between studies. In addition, a control station outside the AR field is frequently lacking, and interpretation of change in species richness or density is then impossible, whatever their trends. Similarly, lack of knowledge on the degree of connectivity between ARs and natural areas does not allow understanding if the local ineffectiveness of some ARs is due to the AR itself (e.g., design, implementation) or just to a low level of connectivity. Consequently, to determine the most efficient AR design or to quantify the AR efficiency to sustain fisheries becomes a challenge. Oppositely, the effectiveness of ARs for artisanal fishing is deeply linked to AR's management. A management failure (e.g., irregular, absent, or insufficient surveillance) can involve significant poaching (Bodilis et al., 2011).

Perception of artificial reefs by users

Before 2000, only one study dealt with the perceptions of artisanal fishermen concerning ARs (Collart & Charbonnel, 1998); since then just two studies have addressed the subject (CREOCEAN, 2003; Leleu et al., 2012). These latter surveys focused on knowledge of the existence of the Côte Bleue Marine Park and the Aigues-Mortes ARs and their specific location. They also dealt with perceptions of the anti-trawling effects of the ARs and determined whether fishermen used them. For Aigues-Mortes, all the fishers knew the existence of the ARs, but more than 80 % of them did not know their exact location and thus could not use

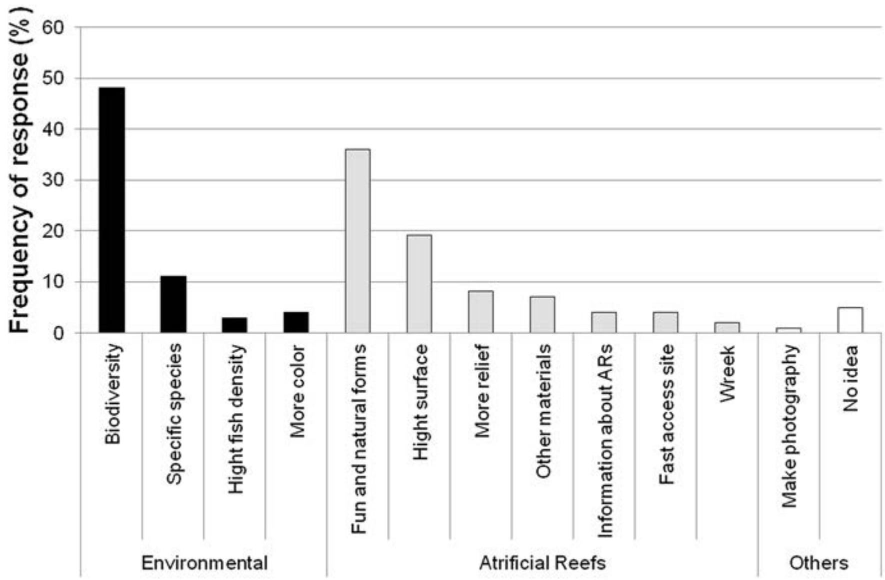


Fig. 10 Frequency response data based on different aspects covered by the sample divers about artificial reefs to the question: For you, what is an artificial reef attractive about your business? The question was open, the responses were coded after and the number of response could be multiple. The survey was realized on 77 SCUBA divers who dived on Leucate-Barcares artificial reefs in summer 2012

them (CREOCEAN, 2003). This study also indicated that half of the fishermen thought that the Aigues-Mortes ARs were efficient against trawling (CREOCEAN, 2003).

For the Côte Bleue Marine Park, all fishermen knew the existence of ARs and were favorable to the deployment of ARs (Leleu et al., 2012). Although the great majority (80 %) of them thought that ARs had a beneficial effect on coastal fisheries in general, 43.7 % indicated that they had no effect on their own activity against 19 % reporting a positive effect (Leleu et al., 2012).

Evaluation of economic and social issues regarding professional fishermen has not been conducted, yet it is important because the principal objective of the majority of ARs is to enhance artisanal fishing (Barnabé et al., 2000). Until recently in France, the deployment of ARs was associated with artisanal fishing because (i) it is these stakeholders who originate requests for AR deployment and (ii) the main financial source comes from the specific fisheries EEU fund, except in few cases where recreational fishermen helped motivate AR deployment locally on the French South Atlantic coast (Barnabé et al., 2000).

Currently, user views of ARs are changing and becoming broader. ARs have been mono-use and are becoming more multi-use. ARs were recently shown to be progressively appropriated by different users of the sea and not simply as a tool reserved for professional fishermen (Tessier, 2013). Recreational fishermen, SCUBA divers, and spear fishermen frequent the ARs more and more, and do not necessarily have a negative point of view of ARs. An ongoing study of the perception of divers about the ARs of Languedoc-Roussillon shows that an AR must meet three criteria to be attractive to this type of user (Fig. 10) (A. Tessier, pers. Comm). There, SCUBA divers seek an AR with a surface permitting a time of diving around 35 min, with unusual or unique forms which merge with the natural environment, and which offer a certain level of biodiversity. Few studies address the non-professional uses of ARs (see Dalias et al., 2012), so there is virtually no objective basis to propose management of these activities. This is reinforced by the fact that there are almost never any government measures to supervise these activities. However, as these non-professional activities can interact with professional fisheries, they have to be considered before the implementation of AR monitoring.

Conclusions for reef planning, policy, and research design and emphasis

Based on the status and trends concerning the recent study, utilization, and performance of ARs in France, we propose future axes in agreement with the new French Administration strategic document for artificial reefs implantation (Ministère de l'Écologie du

Développement durable des Transports et du Logement, 2012). These axes concern three broad subject areas: (i) the planning, execution, and reporting of research on ARs; (ii) the ecological structure and function of ARs, both as intrinsic components of marine habitats and also as tools in management of natural resources; and (iii) socio-economic and policy considerations to optimize the use (or non-use) of ARs in conservation, utilization, and restoration of coastal zone ecosystems.

Planning, execution, and reporting of research on artificial reefs

A first step for French ARs will be to define a standard strategy to monitor AR fish fauna, which uses powerful statistical analysis including the definition of variables to assess. Second it would be informative to initiate experimental deployments which adopt a standard sampling plan and best statistical practices. For example, reference AR modules could be used (Bortone, 2006), adapted for Mediterranean fish assemblages. ARs of small volume will permit easy manipulation by scientists. Furthermore, the use of standard modules could permit meta-analysis such as for Marine Protected Areas (Claudet et al., 2008).

Despite a lack of uniformity among monitoring strategies, this review highlighted the idea that most of the ARs are probably efficient in terms of sustaining of fisheries and anti-trawling at short term. However, a demonstration of a long-term positive effect (biological and fishery) of ARs deployment in France has not yet been published. In France, only the ARs of the PACA region have been followed long term. Thus, it is necessary to initiate long-term scientific surveys on all ARs (time greater than 5 years), as in some other countries (e.g., Ogden & Ebersole, 1981; Buckley & Hueckel, 1989; Stephens et al., 1994; Relini et al., 2002; Santos & Monteiro, 2007). This long-term research aspect was recently mentioned as a desire by the French government (Ministère de l'Écologie du Développement durable des Transports et du Logement, 2012), which would be consistent with several other countries. As the concession of AR is on more of 5 years (between 15 and 30 years), it is necessary to allow a rigorous survey.

The problem of lack of peer-review publications addressing ARs might be solved with engagement of scientists by managers or private companies in charge of scientific surveys. The French scientific community working on ARs is small, and it rarely initiates AR projects in contrast with, for example, Portugal. One solution is the creation of a network including scientists, managers, and private companies either building AR or able to make a scientific survey. This would facilitate exchange of experience and data.

Solving these problems (study design, duration, and quality control) will enhance the scientific knowledge base for the marine ecosystem and thus improve coastal resource use, conservation, and management. This concept is now included in the new document of French administration, under the auspices of the recently renamed Ministère de l'Écologie, du Développement durable et de l'Énergie.

Ecological structure and function of artificial reefs, as (i) intrinsic components of marine habitats and (ii) tools for management of natural resources

The different types of AR modules deployed do not signify a real diversification of research topics, but rather they represent an increase of experimental approaches focused on evaluating AR design. In France de development of lot of type of modules is to develop ARs that offer a range of heights of habitats, adapted to a lot of species, sure to promote increased biodiversity, and the presence of some target species such as sparids and top predators. This contrasts with the Japanese concept that matches one type of AR for one "target" species or a group of species. There is also currently a reflection on the design of AR modules to optimize the recruitment of fish juveniles. This ongoing phase of experimental analysis of AR design is clearly linked to the main objective of most of the immersed ARs: to sustain artisanal fishermen.

For the future, assessment of the complexity of ARs is in order to explain habitat influence upon fauna and flora. One approach is to develop a complexity indicator. This indicator would emerge from the subjectivity aspect, as addressed in other countries this last decade (Sherman et al., 2002; Hunter & Sayer, 2009; Hackradt et al., 2011). Currently, new technologies in sonar acquisition or data processing likely will allow developing a theoretical model of complexity of artificial habitat (Stone et al., 2009). Underwater stereo video (Bellavia et al., 2006) or photogrammetry (Drap et al., 2013) is also promising tools to develop the habitat complexity indicators.

Another fundamental topic is the connectivity between ARs and between ARs and natural habitats. Understanding connectivity will allow (i) improved implementation of ARs (areas with numerous ARs, relative localization of ARs within natural habitats), and (ii) their use as tools to mitigate habitat fragmentation under anthropogenic pressures. Use of acoustic tagging and passive or active tracking methods is reflected in a study of ARs off Leucate-Barcarès (Koeck et al., 2013). Additional experiments are needed in France, as elsewhere (see Jørgensen et al., 2002; Lino et al., 2009; D'Anna et al., 2011). Another aspect of connectivity is availability of habitat for both adult and juvenile phases in area where the ARs have been deployed. Seascape approaches have to be integrated in future planning of ARs deployment (Cheminée et al., 2014). This aspect is rarely studied (Leitão et al., 2009), except maybe in Japan but it is difficult to obtain the information.

Since ARs are being considered as an ecological restoration technique, it seems important to understand the roles they really play, and in what proportion: refuge, reserve effect, nutrition zone, reproduction zone, corridor, etc. Cresson et al. (2014) showed that ARs serve certain fish species as a nutrition zone, and Koeck et al. (2013) showed that white sea bream use specific ARs as definitive refuge year around, while other ARs are occupied according to a temporary pattern (corridor). It means that ecological studies of surrounding soft bottom have to be integrated into AR research. It will be interesting to begin monitoring community surrounding of natural habitats (e.g., seagrass bed, soft-bottom), because they can interact with the AR; the effects of AR are not always positive for the surrounding meiofauna (Danovaro et al., 2002; Fabi et al., 2002; Wilding, 2006).

Socioeconomic and policy to optimize the diverse use of artificial reefs

The last decade has been marked by an emergence of recreational use of ARs. Designs of ARs for fisheries and for SCUBA diving are fundamentally different, but, until now, no project has been specially designed for SCUBA divers in France. This topic will probably be a key point to develop in the future because some ARs are already used for SCUBA diving inducing potential uses conflicts (A. Tessier, pers. obs.). The diving aspect of ARs has been studied in other countries where the recreational aspects of ARs have existed for a long time, e.g., USA, Canada, Australia (Branden et al., 1994; Ditton et al., 2002).

It will be also interesting to develop perception inquiries for all potential user types to evaluate the usefulness of ARs (Cripps & Aabel, 2002; Ditton et al., 2002; Kirkbride-Smith et al., 2013). Cost-benefit analyses have to be implemented in the next decade to assess the economic impacts and the usefulness of ARs as tools in integrated coastal zone management. This aspect is difficult to study (Milon et al., 2000). One protocol of socio-economic evaluation is based on personal interviews using a combination of open-ended (in majority) and closed questions (Bunce et al., 2000; Grawitz, 2000). All potential stakeholder users must be considered. It is necessary that the socio-economic sampling plan is elaborated by experts with relevant sections (Tessier, 2013). Such methods have been already used in other countries and have shown the necessity to control the pressure of users (Whitmarsh et al., 2008).

The "democratization" of AR use requires a management plan to conserve their potential benefits. Thus, whatever the design of the ARs, their efficiency will be directly linked to the management of the area concerned (in particular patrolling and enforcement, but also information on regulation). Most authorities agree about the necessity to implement effective management of MPAs to protect biodiversity (e.g. Pomeroy et al., 2005; Guidetti et al., 2008). Similarly, implementation of ARs needs to be associated with an effective management approach to ensure that the positive effects of ARs will be persevered. The lack of management on the majority of ARs was mentioned during the 1st Euro-Mediterranean Conference about the management of ARs (Ville de Marseille, 2013a). French administration of coastal resources states that management is now an obligatory action in AR deployment (Ville de Marseille, 2013b). Future AR managers must be integrated into their management proposal very early in the reflection.

Having socio-economic evaluations will permit managers of ARs to propose policy measures knowing their acceptability to the AR users. The regulation measures concerning ARs zones could be based on measures applied in Marine Protected Areas, and include a No-take zone, a limitation of frequency by user types, and a catch quota. The elaboration of effective management of French ARs is one of the main challenge of the second part of this decade for ARs.

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