Chapter 20

Restoration of fish habitats, populations, and communities

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20.1 Restoring marine fish: Utopia or real challenge?

The actions of humans in the ocean, such as fishing and aquaculture, have profound effects on marine ecosystems, impacting the growth and regeneration of marine life. To achieve the sustainability of fisheries and aquaculture, a reduction of these environmental impacts is necessary (Bastardie et al., 2024). Among marine resources, fish is probably the most at risk considering the heavy impact on its populations due to overfishing, which prevents self-replenishing, and habitat degradation due to human activities (Arthington et al., 2016). In addition to direct human impact, climate change has also a severe impact on the fish communities due to warming, acidification, and oxygen depletion, and the potential synergy between all impacts (Cheung et al., 2021; Fernandes et al., 2013; Pörtner and Peck, 2010). The current status of a large number of marine fish species calls for protection and restoration measures to ensure their survival and further exploitation (FAO, 2022; Piet and Rice, 2004; Teh et al., 2017).

Over the years, several measures have been taken to protect and rebuild marine fish stocks worldwide. The first is based on the regulation of fishing activities in certain areas or for certain species or stages of development, using fishing regulations, quotas, closed seasons, bans on certain gears, and total protection for some species. All these regulations have helped to improve the resilience of marine fish populations, but in many cases, they have not been sufficient to inverse the trends and restore populations to sustainable levels. The establishment of marine protected areas (MPAs) to protect species and restore stocks is probably one of the most widely used methods around the world, but it has also had unexpected effects on species due to cascading effects and increased interspecific competition (Buxton, 2006). The main objective of MPAs is generally to support fisheries by exporting fish produced within the protected area to outside the perimeter of MPAs. In addition, the level of protection offered by a large number of MPAs is not sufficient and does not provide effective protection for the restoration of the species concerned. The establishment of no-take areas in MPAs may have a direct effect, not only on the fish community but also on their habitat (Hopf et al., 2022). On a smaller scale, artificial reefs are often used around the world as a means of increasing fish populations, with some success when compared to control areas (Bracho-Villavicencio et al., 2023; Granneman and Steele, 2015; Santos and Monteiro, 2007; Song et al., 2022). This method should be seen as a complementary tool for mitigating various human impacts and could be used to restore habitat heterogeneity where habitats have been damaged by mining, harbor extension, trawling, and overfishing in general. Several habitat restoration actions were experimented with to restore marine fish by reestablishing seagrass beds and seaweed. These actions have been carried out by various means (transplantation, seed planting, special protection) and have had several positive effects on the local fish habitat and potential spin-offs for fishing activities.

All these first actions for marine fish restorations are mainly devoted to coastal and shallow water habitats. If we consider species that do not have any developmental stage in the shallow coastal area and stay principally offshore, it becomes more difficult to implement actions likely to support these fish species. Therefore, regulations are becoming the only means of protecting species with a view to their self-restoration to a sustainable level. The restoration of marine fish has also been attempted using aquaculture for restocking actions. This aquaculture-based enhancement technique has been used for over a century (Kitada, 2020). It consists of releasing farmed juvenile fish to increase the natural population. It has been considered in

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several countries as a method of enhancing fish stock, increasing fisheries productivity, restoring populations that were not viable, and creating new fisheries. This technique has also suffered for decades from a lack of studies evaluating the effectiveness of restocking (Howell et al., 1999) which has led to a poor image and a slowdown in its use. In more recent years, studies that assess the effectiveness of hatchery-released fish in contributing to the enhancement of the population have been carried out (Taylor et al., 2017; Kitada, 2020) and show different success and limitations due to species' life history and vulnerability to fishing. A persistent problem is the lack of suitable monitoring and assessment methods although trials have been carried out with eDNA (Osathanunkul and Suwannapoom, 2023). Population support through restocking has been used for marine fish (Kitada, 2020) and for diadromous species that spawn in freshwater but live most of their lives in marine environments.

Actions to restore marine fish are not simple and straightforward, as nothing seems to be "the" solution to the problem of declining fish numbers in a multitude of marine environments. The true effectiveness probably lies in the combination of different techniques (fishing regulation, habitat protection, habitat restoration, habitat creation, and restocking) already used in seas around the world, but great attention must be paid to the interaction between human actions in favor of the fish community and the wild world in which they take place. Successful restoration of marine fish is not a utopia, but rather a genuine commitment.

This chapter presents some examples of techniques used for restoring habitats for fish or for restoring populations themselves. It presents the advantages and limitations of each method to help understand the capacity of the method and the type of species that may benefit from such actions.

20.2 Fish habitat restoration

One of the possible levers for restoring marine fish is to restore and protect some of the species' essential habitats. Spawning and nursery habitats are among the most important habitats that should be protected and eventually restored when they have been damaged by human impact. Physically restoring fish spawning and nursery habitats can be complicated, but strong legal protection of habitats should be the minimum where they are known (Hopf et al., 2022). Depending on the species, spawning and nursery habitats can be very different, ranging from hard-structured substrate to sand or vegetated areas. All these types of habitats can be restored or, preferably protected when a fish population shows signs of weakness. Restoring habitats often means restoring complexity (Schulz et al., 2020). Where natural marine reefs have been degraded, artificial boulder reefs can partially restore the original functionality of this habitat for fish (Kristensen et al., 2017). Oyster reefs, rocky areas, seaweed restoration, and artificial structures are among the potential habitats that could be used to restore essential fish habitat. Restoring mangroves and coral reefs can also be part of fish habitat restoration, which can help coastal, estuarine, and lagoon fish populations to thrive for the benefit of the local community, but actions to restore these habitats are more akin to protecting an overall ecosystem. Restoration measures involving the planting of mangrove seedlings or coral branches can help to improve the habitat, but it is the previously mentioned protection measures that will allow species in difficulty to return.

20.2.1 Seagrass habitat restoration

Seagrasses are marine angiosperms that serve as habitats for rich communities and play critical physical roles in the coastal areas, not only providing well-acknowledged ecosystem services for food production but also for combating coastal erosion. Their floral diversity is relatively low, with only about 72 species distributed in all continents but Antarctica. Their three-dimensional structure of the roots, rhizomes, and shoots is an attractor for a high diversity and abundance of other organisms. They are exposed to several threats that determine a declining global trend, leading to the acknowledgment that conservation measures alone are insufficient to achieve the necessary recovery. There is an urgent need to implement large-scale restoration actions (Buelow et al., 2022; Cullen-Unsworth and Unsworth, 2018).

The increased attention to the status of seagrass ecosystems is fueled by their role in supporting human well-being through livelihood provision and food security for many coastal communities (Unsworth and Cullen-Unsworth, 2016). Seagrasses support both coastal and offshore fishery, including 21.5% of the catches from the 25 most landed species. It supports small-scale fishery as fishing ground or as the provision of nursery and trophic resources for adjacent fisheries (Unsworth et al., 2019). Nevertheless, fishery is one of the most significant impacts on seagrasses, particularly due to the direct action of fishing gear (Buelow et al., 2022; Herrera et al., 2022).

Although seagrass is utilized as food only by a few fish species, many more species show a strong association with seagrasses, with the meadows providing a breeding ground, essential refugee, and trophic habitat based mostly on the seagrass-canopy inhabiting invertebrates. Within the seagrasses beds, species composition, leaf height and density, and seagrass cover can influence the characteristics of fish assemblages, with some fish species preferring homogeneous meadows with high leaves canopy and cover and others being more abundant in less dense seagrass meadows (Scapin et al., 2018a; Whitfield, 2017). Also, at a larger spatial scale, the spatial configuration of seagrass patches and other habitat types along the environmental gradients influences the expected characteristics of the fish assemblage (Scapin et al., 2018b; Staveley et al., 2017), and hence also their role as nursery areas or as support for fisheries (Nagelkerken et al., 2015; Scapin et al., 2022). Understanding how the configurations at the local and seascape scale of seagrass meadows influences the fish assemblage represents a very relevant feature to consider when planning the expected outcomes of a restoration project.

Seagrass transplantation schemes can be included in more complex restoration schemes, such as the restoration of natural gradients by acting on hydrological processes and physical-chemical conditions in coastal or transitional areas (e.g., Boscolo Brusà et al., 2022; Claassens et al., 2022). This can also be motivated considering that an improvement in environmental conditions can increase the likelihood of restoration success for seagrasses, as nutrient load, turbidity, and algal bloom can affect the restoration as much as they can be detrimental to natural seagrass meadows (Sfriso et al., 2021; van der Heide et al., 2007).

The restoration actions are normally based on replanting adult shoots or seedlings. Transplants are often collected in the wild as seeds and plants grown in the laboratory are rarely available in quantities useful for restoration programs. Seagrasses can be collected from donor sites as fragments broken off from live plants, as whole cores of seagrass, including sediments, or as fragments collected on the shore. The collection and transplant can be done manually or mechanically, according to the characteristics of both the donor and the restoration sites, as well as the restoration plans (Curiel et al., 2021; Gamble et al., 2021).

Temporal periods required for full restoration may exceed typical monitoring periods, potentially leading to an underestimation of the actual benefits. This is particularly evident moving beyond the targets of habitat structure and considering the implications of ecosystem response. Nevertheless, successful seagrass restoration led to a quick response of fish assemblages in coastal areas, estuaries, or coastal lagoons. The recovery of diversity composition and abundance of fish has been observed for the Biscayne Bay, Florida, United States (Thorhaug, 1987); the coastal bay of Corpus Christi, Texas, United States (Sheridan, 2004); and the Gulf of Mannar, Southeast India (Edward et al., 2019). In the Venice lagoon, the ecological status assessed with a fish-based index shows notable improvement as early as 2 or 3 years after the beginning of the transplantation scheme (Sfriso et al., 2021).

Seagrass restoration is crucial for the conservation and management of coastal habitats and the associated ecosystem services. The optimal scheme of intervention should be planned at a local scale, adapting to the specific environmental conditions, taking into account also the desired state and the socio-economic context (Boscolo Brusà et al., 2022). However, it is clear that it is becoming more and more important to rely on objectives and success criteria associated not only with the structure and characteristics of the vegetation but also with the desired responses of the communities and expected ecological functions and ecosystem services.

Given the importance of seagrass in the functioning of coastal ecosystems, several restoration programs have been set up around the world (Seagrass Ecosystem research & Restoration program for MOTE in Florida USA https://mote.org/research/program/seagrass-ecosystem-research-and-restoration-program/initiative-progress-seagrass-initiative, Seagrass restoration initiative in Wadden sea, NL (Govers et al., 2022)). Local knowledge of the fish assemblage association to seagrass characteristics may contribute to defining the overall goal and specific success criteria (Scapin et al., 2016) that should be considered during project planning and design.

20.2.2 Bivalve reefs habitat

Reef ecosystems host abundant and diverse marine communities across the globe, with marine fishes being some of the most prominent and charismatic residents within tropical and temperate reef ecosystems. Reef-building bivalves (e.g., mussels and oysters) are ecosystem engineers, implying that they modulate the biological and physical components of their surrounding environment and thereby maintain or create habitats to the benefit of marine organisms, including fish. For example, the vertical accretion of bivalves creates complex three-dimensional reef structures (Walles et al., 2015) that enhance shelter availability for reef fishes (i.e., autogenic engineering). In addition, the filter-feeding ability of individual bivalves contributes to benthopelagic coupling, locally enriching nutrients in the surrounding sediment through biodeposits (i.e., allogenic engineering) and thereby shaping macrofaunal communities that constitute prey items for higher tropic levels, such as reef fishes (Sea et al., 2022). Bivalve reefs are currently under intense pressure from human activities and are facing widespread declines in many parts of the world (Beck et al., 2011; zu Ermgassen et al., 2020), with associated losses of the important ecosystem functions they offer, including water filtering, regulation of nutrient dynamics, habitat provision, and coastal protection. In particular, overfishing and destruction caused by commercial dredge fisheries have in many places resulted in the functional extinction of bivalve reefs and a subsequent collapse of the fisheries (zu Ermgassen et al., 2020). However, in cases where fisheries collapsed, this has mostly not resulted in a subsequent recovery of bivalve reefs as dredging activities permanently remove both living and nonliving shell material and other hard substrates required for bivalve settlement, while simultaneously exacerbating sedimentation and declining water quality (Beck et al., 2011; Howie and Bishop, 2021). Additional stressors, including impacts from other mobile fishing gears, diseases, pollution, and coastal development, have also contributed to the decline in bivalve reefs in some areas (zu Ermgassen et al., 2020). The associated loss of reef area, vertical relief, and structural complexity directly affect the habitat quality for reef fishes through reduced shelter availability and food provision, while simultaneously impacting connectivity and nursery function within the wider coastal seascape. As such, the degradation or removal of bivalve reefs can have detrimental effects on fish populations and is often associated with declines in fish abundance and diversity, thus negatively affecting landings of commercial and recreational fish species (Gilby et al., 2018).

The ongoing global decline of bivalve reefs has recently catalyzed efforts to restore bivalve habitats in many parts of the world, although restoration techniques were already being developed in the United States in the 1990s (zu Ermgassen et al., 2020). Bivalve reefs can be restored using various methods including seeding, i.e., introducing spat (juveniles) that have settled on shells or similar substrates in hatcheries, or by transplanting adult bivalves originating from aquaculture, disease-resistant breeding programs, or the wild (active restoration; Howie and Bishop, 2021). In some cases, e.g., for intertidal mussels and mixed bivalve beds in the Dutch Wadden Sea, the protection of areas suitable for recruitment may yield higher recovery rates relative to large-scale restoration efforts (passive restoration; zu Ermgassen et al., 2020). Many of the factors determining the development of restored bivalve reefs also directly or indirectly govern the survival and growth of associated fish species (Gilby et al., 2018). For example, sedimentation rates are inversely related to bivalve growth and condition due to clogging of gills and impaired filter-feeding, while sustained exposure to high turbidity levels has harmful effects on juvenile fish growth and health and may hamper the use of visual cues in predatory fishes. This highlights the importance of careful site selection within restoration efforts to avoid areas with frequent high turbidity levels and thereby cobenefit bivalve development and subsequent colonization by fish (Gilby et al., 2018). In addition to environmental factors, the structural attributes of restored bivalve reefs are an important determinant of reef development and resilience, and likewise for the provision of suitable habitat for fish species. On the scale of individual reefs, structural complexity in the form of crevices, holes, and ledges create microhabitats that protect bivalve recruits from predation or environmental stressors, while providing a similar refuge function for small-bodied reef fish (Fig. 20.1). Although some bivalve species (e.g., mussels) can settle on conspecifics in soft-bottom areas, bivalve restoration often requires a hard substrate available for settlement. This can be facilitated by selecting sites with naturally occurring hard bottom, by deploying artificial structures (e.g., biodegradable mesh sheets, BESE-elements), or by deploying natural substrate (e.g., boulders) in areas where this habitat type is scarce or historically cooccurred with bivalve reefs. The latter option, a concept also known as "multihabitat restoration," is particularly noteworthy since the practice of deploying boulders before restoring bivalve reefs is already conducted in many cases, yet often without the recognition that two unique habitat types are being restored (Liversage, 2020). While each habitat provides its own structural attributes and set of ecosystem functions, they can also function synergistically to promote reef development and resident fish communities. For example, boulder habitats undergo minimal disturbance (e.g., overturning) when exposed to hydrodynamic forces (e.g., at intertidal habitats) and thereby reduce shell degradation among adult bivalves while facilitating continuous recruitment in dynamic environments (Liversage, 2020). Conversely, bivalves constitute a direct food source for higher trophic levels and their gregarious settlement can result in reef development beyond the initial restoration site, expanding suitable habitat conditions for fish species associated with boulder habitats. Bivalves offer microhabitats for juvenile and small-bodied fishes, while cavernous structures of boulder reefs provide suitable habitats for large-bodied fishes (Wilms et al., 2021), implying that multihabitat restoration can host a higher diversity of resident reef fishes, relative to restoring these unique habitat types in isolation.

On the wider local or regional scale of coastal habitats, the location of restored bivalve reefs in relation to the surrounding coastal landscape (i.e., seascape) is an important determinant for reef development and subsequent colonization by fish species (Fig. 20.1A). Selecting restoration sites with a high degree of connectivity within the wider seascape can promote the supply and settlement of larvae from wild bivalve populations, as well as fish larvae dispersing from other nearby coastal habitats. Bivalve reefs can also contribute to facilitative (i.e., positive) interactions between different habitat types within the coastal seascape, for example, by improving water quality through filter-feeding and sediment enrichment via biodeposits, two mechanisms that can promote seagrass development that also act as essential habitat for fish (Reeves et al., 2020). Consequently, strategically positioning restoration sites within well-connected coastal mosaics of diverse habitat types can benefit the abundance and diversity of fish species, in particular, those that undergo ontogenetic shifts in habitat use, and can facilitate fish movement by providing stepping stones for inshore-offshore migrations (e.g., for feeding or spawning; Gilby et al., 2018). Furthermore, predation rates on restored bivalve reefs can be significantly reduced when positioned closer to structurally complex habitats (e.g., seagrass meadows and mangroves) relative to isolated reefs

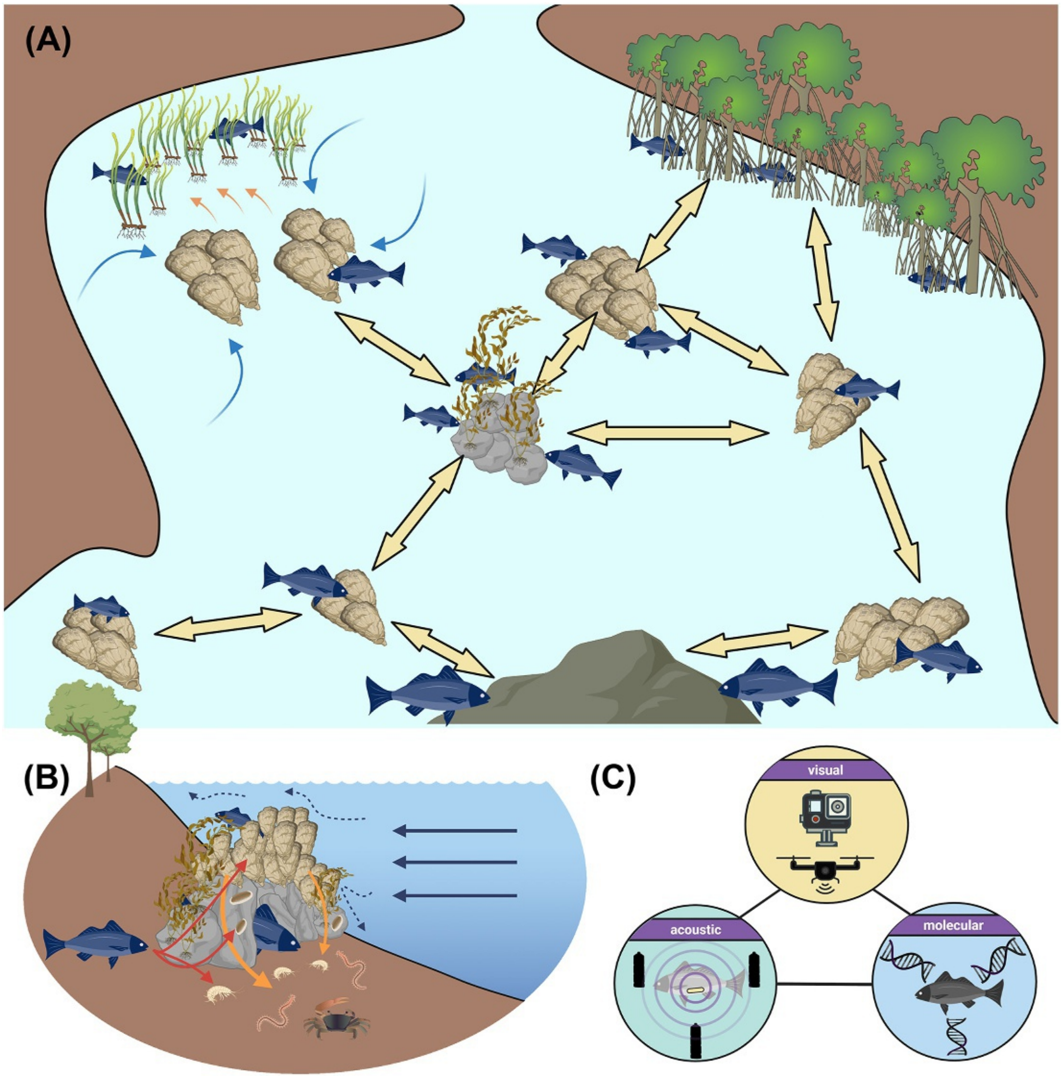

FIG. 20.1 Conceptual figure illustrating the benefits of bivalve reef restoration for marine fishes and methods used to monitor fish dynamics at restored habitats. (A) Example of restoring bivalve reefs within a seascape context. By carefully considering the location of restoration sites within a seascape context, restored bivalve reefs can act as stepping stones that facilitate fish movement between different types of coastal habitats and inshore-offshore migrations *(yellow arrows)*. Bivalve reefs can also contribute toward facilitative interactions with adjacent habitats, e.g., by improving water quality through filter-feeding *(blue arrows)* and sediment enrichment via biodeposits *(orange arrows)*, thereby creating favorable conditions for seagrass meadows. (B) Example of multihabitat restoration after Liversage (2020). Boulders create a stable foundation of hard substrate to promote bivalve settlement and growth, while the vertical accretion of bivalves attenuates current velocity and wave energy *(blue arrows)*. Fish may feed on a variety of food items offered by corestored boulder and bivalve reefs *(red arrows)*, including direct consumption of bivalves (by molluscivorous fish), boulder-associated fauna (e.g., chitons), or benthic fauna on surrounding soft sediment enriched in nutrients through biodeposition *(orange arrows)*. The spatial arrangement of bivalves creates microhabitats where juveniles and small-bodied fishes can find refuge, while cavernous structures between boulders can provide shelter for larger fish species. (C) Noninvasive monitoring methods that can be employed, or ideally combined, to document restoration effects on resident and transient fish communities. *((A) After Gilby, B.L., Olds, A.D., Peterson, C.H., Connolly, R.M., Voss, C.M., Bishop, M.J., Elliott, M., Grabowski, J.H., Ortodossi, N.L., Schlacher, T.A., 2018. Maximizing the benefits of oyster reef restoration for finfish and their fisheries. Fish Fish. 19, 931–947. https://doi.org/10.1111/faf.12301. Created with BioRender (www.biorender.com). Additional symbols courtesy of the Integration and Application Network (https://ian.umces.edu/media-library/symbols/).)*

surrounded by unstructured seafloor (Duncan et al., 2019), while promoting habitat diversity in well-connected systems reduces competition for space and food sources for fish at adjacent habitats (Gilby et al., 2018). These interconnected effects suggest that careful consideration of seascape context in restoration efforts can strengthen the nursery function of coastal habitats and have the potential to maximize outcomes for bivalve reefs and associated fish communities. As such, restoration efforts aiming to cobenefit fish populations alongside bivalve reef development should critically consider the availability of habitats within a wider seascape context, as well as the movement and migration patterns of target fish species (Gilby et al., 2018). Such efforts could be complemented with biophysical models that couple hydrodynamics with pelagic larval duration to understand bivalve sink-source dynamics, or with bioenergetic models that simulate trophic energy flow to predict the biomass of resident and transient fish species under various restoration scenarios (McCoy et al., 2017).

A key component of habitat restoration efforts includes the evaluation of different methods and effects on biological communities through well-designed monitoring programs. Generally, restoration efforts are carefully planned in advance and initiated at established periods, in contrast to natural or anthropogenic impact events for which the onset can be hard to predict. In terms of measuring effects on biological (e.g., fish) communities, this implies there is an opportunity for baseline monitoring (i.e., before the restoration is initiated) that is often lacking in impact assessments (e.g., following wildfires or oil spills) and that can serve as a reference to the preimpact (or prerestoration) state. In addition, communities at restoration sites should be compared to those at control areas that reflect the initial (negative control) or the anticipated (target reference) system state, across time. The resulting sampling design, also known as a before-after control-impact (BACI) design, allows for disentangling natural system fluctuations from the impact effect and thereby outperforms simpler designs in terms of detecting the true effect's direction and magnitude (Christie et al., 2019). Monitoring of marine fishes can be achieved using a variety of sampling methods. However, many conventional methods are based on the extraction of fish (catch-based surveys) and may be destructive to the benthic environment (e.g., in the case of bottom trawling), making these methods unsuitable for monitoring restored habitats. Instead, a variety of visual (Sheehan et al., 2020), acoustic (Mooney et al., 2020), and molecular techniques can be employed, or even combined, to gain insights into restoration effects on fish communities in a noninvasive manner (Fig. 20.1C). Combined, the strengths and pitfalls related to visual, acoustic, and molecular methods highlight the potential to obtain complementarity through their combined use and thereby gain a more holistic understanding of fish dynamics at restored habitats. This will ultimately allow restoration managers, practitioners, and scientists to effectively allocate limited resources and optimize restoration strategies to cobenefit marine fishes alongside bivalve populations.

20.2.3 Artificial reefs: A lure or an effective solution

According to the Committee on Biological Diversity in Marine Systems (1995), fishing and physical habitat alterations are among the pressures that most affect the loss of marine biodiversity. Fishing activity directly affects species of commercial interest, influencing the size of their populations, the average size of individuals, their genetic diversity, and their reproductive potential having brought many of them to the brink of extinction. While most of the biological effects show resilience and communities can recover by reducing pressures, habitat destruction is usually irreversible and affects the entire community, preventing its recovery. Due to this, the construction of artificial reefs has been considered an important management tool for the restoration of marine ecosystems (Pratt, 1994).

Constructed of a variety of materials, including waste, and in a myriad of designs and sizes, artificial reefs are a way of altering the structural complexity of the environment to increase the local abundance of one or more species or protect habitats from the erosive effects of trawling. For this reason, they are usually installed in areas that have low structural complexity and are not very deep.

Throughout the history of systematized reef implantation, which dates back to late 18th century in Japan, a country that also launched their extensive use and technological advances in the 20th century (Grove et al., 1994), small-scale artisan structures, waste materials, and local effect have given way to projects that cover stretches of coastline of even dozen kilometers, with sophisticated designs and special materials (Seaman and Sprague, 1991; Ramos et al., 2007; Relini et al., 2007).

In principle, the functioning of these structures is based on the fact that they offer substrate to sessile species, new habitats for the recruitment of larvae and juveniles, and refuges for adult individuals, both predators and prey. The fact that colonization by fish takes place in a few days, while that of invertebrates or algae may require months (Bohnsack and Sutherland, 1985; Bohnsack et al., 1994), suggests that shelter needs are more important than food (Pérez-Ruzafa, 1995) or that the structural complexity of the habitat acts as an innate attractor for the species (García Charton and Pérez Ruzafa, 1999).

Although size of the reef can determine the age structure of the assemblage (Bohnsack et al., 1994), the concentrating action of biomass seems to be directly related to their complexity, the number of blocks that make up the reefs, and the height reached from the bottom (García-Charton and Pérez-Ruzafa, unpublished data) so as the age of the reef, location, and presence of seagrass meadows in the surroundings (Relini et al., 2007).

In addition to the materials used, the design and spatial layout of the modules that constitute an artificial reef can improve their functioning, as can the installation of simulated macroalgae (Vega Fernández et al., 2009), or the guarantee of connectivity between installations and with natural reefs (Vega Fernández et al., 2008).

Since the first studies, the rapid colonization of reefs by adult fish, to a large extent predators, and the doubts about the existence or not of recruitment in the reef structures, increased the suspect that artificial reefs acted as "predators" for juveniles and mere attractors and concentrators of population and, therefore, facilitating and increasing the effects of overfishing (Seaman, 2007). However, although initially the reef acts as a mere attractor, it also shows nursery function (Pastor et al., 2013) and in the medium and long term, its effect is to increase the carrying capacity of the system, admitting a greater density of individuals (both of recruits and adults) than in natural habitats due to the greater structural complexity, favoring, therefore, a global increase in the abundance and biomass production (Diamant et al., 1986; Sherman et al., 2002; Santos and Monteiro, 2007; Edelist and Spanier, 2009; Pastor et al., 2013; Cresson et al., 2019).

For this reason, artificial reefs can be used as a measure to recover seabeds whose three-dimensional spatial structure has been simplified by the effect of trawling gears (Turner et al., 1999), as well as a way of increasing the heterogeneity of habitats in large stretches of sandy or muddy seabeds, as an attractor for diving activities and a measure to reduce tourist pressure in marine reserves or even as step-stones to facilitate connectivity between marine reserves separated by large flat areas without rocky bottoms. They are also a good management tool that satisfies both, the fishermen and the divers, and reduces conflicts between users (Claudet and Pelletier, 2004; Ramos et al., 2007; Kirkbride-Smith et al., 2016).

In the same way, the introduction of artificial substrates, usually rocky or wooden, in coastal lagoon habitats is particularly successful as it increases the environmental diversity in a mud-dominated environment (Pérez-Ruzafa et al., 2006). They are usually used for the construction of poles, jetties, breakwaters, and dikes. Some of these elements, such as signaling and mooring poles in Venice lagoon, or piers in Mar Menor, form an important part of the typical landscape of these lagoons. Artificial hard substrata are colonized by algae, invertebrates, and fish that otherwise could not inhabit these environments. The breakwater community is similar to those living on natural lagoon rocky bottoms at their outlet, both in terms of species composition and assemblage structure, even with higher population density, as the structural complexity of artificial constructions usually is greater than that of the natural rocky substrates, favoring the abundance and specific richness of the assemblages. Studies in the Mar Menor lagoon show that colonization takes place in a few months after the installation of artificial substrata.

However, beyond the positive effects of these man-made structures, it should be considered that depending on their design and size, structures such as breakwaters built for harbors and beach creation, can modify the hydrodynamic regime in the surrounding areas, and sandy bottoms could be substituted by muddy ones as a consequence of the processes of sedimentation and modify the fish composition (Pérez-Ruzafa et al., 2006).

The effectiveness of reefs as protection against trawling depends on the design of the modules (shape, weight, etc.), their number and distribution on the bottom, and the surveillance measures adopted to prevent intentional displacement of the blocks by trawlers to open up paths for fishing.

20.3 Restoring fish population: The case of diadromous species

Diadromous species are composed of three types, they gather anadromous species (reproduction and early growth in freshwater and most growth at sea), amphidromous species (reproduction in freshwater, larval drift to sea for early growth and most growth in freshwaters), and catadromous species (reproduction and early growth at sea and most growth in freshwaters) (McDowall, 1997). Their decline is notably linked to the fact that they need to migrate between freshwater and saltwater habitats and along transitional waters of different sizes; thus, they encountered the cumulated threats of those different habitats along their journey. The trend can be illustrated by the decline of most North Atlantic diadromous species with a sharp decrease in the number of populations in the last century and an increase in the number of species with an endangered status (Limburg and Waldman, 2009). For example, for anadromous species of known status, more than 30% are considered extinct or threatened (from critically endangered to vulnerable) (Acolas and Lambert, 2016).

Conservation and restoration of those diadromous species is thus a primary goal of this century illustrated by the increasing proportion of literature focusing on these topics that represented about 20% of the scientific articles in the 1990s to reach about 45% of the literature around diadromous fish nowadays (Fig. 20.2).

For most diadromous species, the freshwater phases are the most well-known and there are knowledge gaps in estuarine and sea environments, as illustrated by Pacific salmon case studies (Flitcroft et al., 2019).

Thus, most restoration studies occur in freshwaters and they can lead to local action either on the land or directly in the rivers. An example of action on the land is acting on the riparian vegetation to control the shade to reach the species' environmental requirement (e.g., Leathwick et al., 2009; Mollot and Bilby, 2008). Restoration can be performed directly in the river by reconstructing spawning ground characteristics for some species in small streams through artificial habitat addition (e.g., Hickford and Schiel, 2013) or by restoring substrate integrity through the importation of new material or cleaning clogged substrate (e.g., Pulg et al., 2013). The most common restoration action in freshwater is to improve connectivity by constructing fish passes

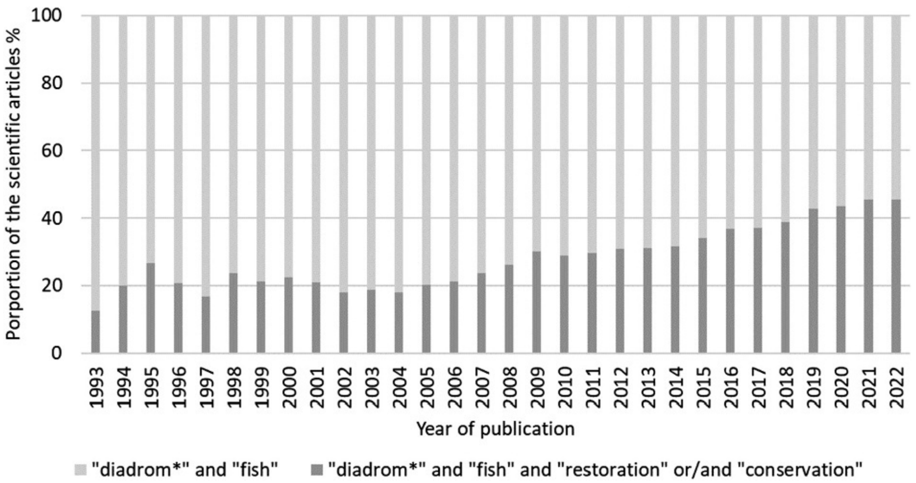

FIG. 20.2 From 1993 to 2022, the evolution of the proportion of scientific articles including conservation and/or restoration topics among diadromous fish literature. Using Web Of Science, field "topic," the three following queries were added to illustrate articles dealing with conservation and or restoration of diadromous fish (total = 274): "diadrom*" and "fish" and "restoration" not "conservation" + "diadrom*" and "fish" and "restoration" and "conservation" + "diadrom*" and "fish" and "conservation" not "restoration." The following query allowed gathering general literature on diadromous fish: "diadrom*" and "fish" (total = 602 articles). The relative proportion of the corresponding article was then represented in this figure in percentage of articles. This figure intends to illustrate the relative proportion of the topic of interest using restricted and consistent keywords along the years; it does not intend to be an exhaustive literature review.

to ease the migration between spawning ground and growth areas but they can have mitigated efficiency (e.g., Kemp, 2016). Furthermore, in some rivers, removing dams has been motivated by the presence of a diadromous population (e.g., Brenkman et al., 2012; Lake et al., 2012; Forget et al., 2018), which could restore the ecosystem functionality beyond the targeted population (e.g., Ravot et al., 2020). In fact, diadromous species' presence could motivate large restoration measures along a watershed when physical and chemical connectivities are in play since those species can serve as flagship species (e.g., Rochard et al., 2009). As suggested by McIntyre et al. (2015), the wave of dam removals in North America and Europe is likely to expand.

At sea, knowledge of most diadromous species is scarce because there are few records of their observation but there are growing studies to increase knowledge with a conservation focus (e.g., Charbonnel et al., 2023; Elliott et al., 2023; Trancart et al., 2014). At sea, mostly conservation measures (i.e., protection of the current state) instead of restoration measures (i.e., coming back to a previous reference state) could be undertaken such as the use of adapted Marine Protected Area (MPA) tools. These tools are already used for other migratory fish species (i.e., not diadromous) and they can protect key habitats by preventing habitat degradation or lowering fishing pressure when the real use of those areas is evaluated (e.g., Kerwath et al., 2009; Breen et al., 2015).

In estuaries, there are few studies on migratory fish restoration since this system is used mainly as a corridor for migration. But for example, the increase of turbidity maximum zone of water with low oxygen in different estuaries is of concern since it forms a chemical barrier to migration for some species (Buysse et al., 2008; Tetard et al., 2016), which advocates for the restoration of water quality. Few diadromous species use the estuary as a growth area (e.g., sturgeons) but their presence militates for the preservation of essential habitat integrity with proposals to limit gravel extraction (e.g., Hatin et al., 2007; Lepage et al., 2000) such as in freshwaters. Like at sea, MPA tools can be used as protection measures (Briggs, 2016).

In different environments, fishing regulation for diadromous fish is one conservation tool commonly used with different levels of restriction. For example, there is a total allowable catch (TAC) limit in Europe calculated each year per watershed for some species such as salmon or eels; a local moratorium can be used such as for Allis shads in the Garonne watershed (Rougier et al., 2012) or total fishing ban such as for European sturgeon in France since 1982. However, when the population is already at low levels, some measures can arrive too late.

One tool also used for restoration is translocation (i.e., human-mediated movement of living organisms from one area with release in another, IUCN, 2013). To avoid the extinction of a species or a population, the number of individuals is then increased artificially in a chosen environment. It can be made by capturing spawners in the wild to reproduce them and release larvae or juveniles in a selected environment (e.g., Borcherding et al., 2010); by capturing juveniles and spreading them in different watersheds such as eels translocation programs (e.g., Stacey et al., 2015); or by stocking fish relying on a relictual captive stock (e.g., Roques et al., 2018). However, the success of such measures is closely linked to the identification of the main reason for the decline and relies on the suppression of the main threats.

To conclude, for diadromous fish, their life cycle depends on a continuum and imposes special constraints on conservation approaches. Therefore, the management tools used for restoration purposes need to be coordinated along the migration pathway (Flitcroft et al., 2019; Munsch et al., 2020). Mostly emblematic species are studied and benefit from restoration projects such as salmonids, sturgeons, eels… and mainly in the Northern hemisphere. Even if the results of restoration actions can be mitigated, those economically valuable migrants can sometimes serve as umbrella species whose conservation will also improve the status of other migratory species or communities but more attention is needed on the other less known diadromous species that can disappear silently.

20.4 Protecting early stage to restore population

Since many years, maritime stakeholders such as environmentalists, fish scientists, MPA managers, fishermen, NGOs, etc., have been assessing, monitoring, administrating, fishing, or caring for adult fish populations but most marine species have a two-phase life cycle. Indeed, most coastal marine animals (demersal fish, crustaceans, mollusks, sea urchins) have an offshore pelagic larval phase at the beginning of their life cycles before moving to the shallow coastal zone (Fig. 20.3) (Leis, 1991; Leis and Carson-Ewart, 2000).

This phase allows them to colonize new habitats, facilitating the species' wide distribution and, consequently, their persistence. The larvae, fairly passive during most of this first phase, become active in search of their new coastal habitat.

It has been shown that during the final phase of colonization, larvae and postlarvae suffer catastrophic mortality rates during the settlement process: more than 90% disappear in the week following colonization (Planes and Lecaillon, 2001; Doherty et al., 2004; Planes et al., 2002). Eggs, larvae, and even postlarvae of marine animals are usually considered nonexploitable marine resources, as opposed to juveniles and/or adults, which are actively harvested. However, it is now fully accepted that, given the very large number of postlarvae arriving from the ocean, collecting a small percentage of them has a negligible impact which is also limited in time (Bell et al., 2009).

20.4.1 Early life history stage (ELHS)

Enhancing the value of young life stages could help reduce the pressures on adult fish by providing access to a new untapped and underexploited marine resource that could be used as an additional means of conservation and restocking resources, especially where conventional conservation strategies have already failed.

Based on knowledge and field experience acquired in postlarvae rearing, companies dedicated to ELHS were

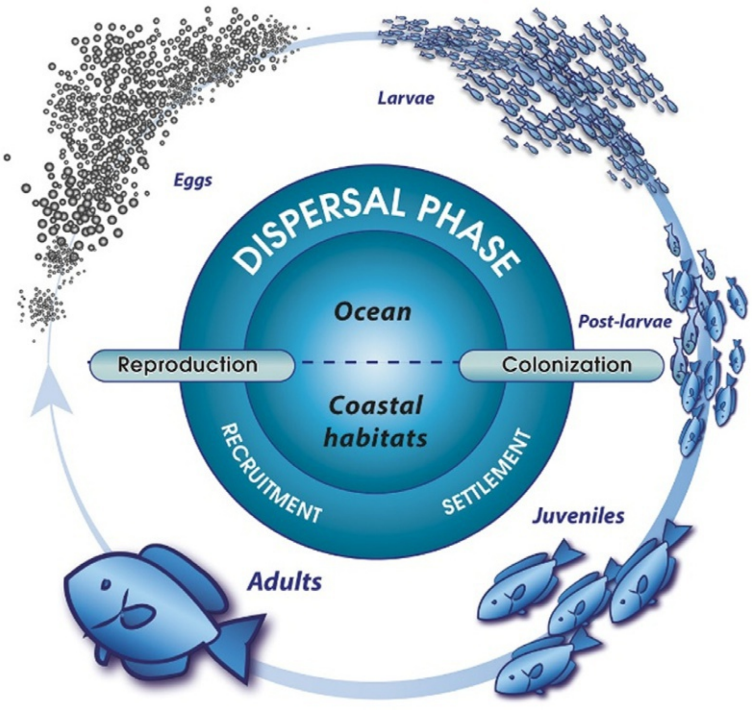

FIG. 20.3 A schematic representation of a demersal fish life cycle.

created in the early 21st century with the aim of developing operational solutions for restoring and repopulating marine ecosystems. Two solutions are today considered operational: artificial fish nurseries within the harbor and fisheries enhancement.

Near-shore infrastructure (e.g., coastal cities with harbors) is becoming increasingly widespread, directly affecting biodiversity and essential shallow marine habitats for the news recruits. Ecosystem processes and functionality can thus be impacted and disrupted by human activities, resulting in a decline in ecosystem health and a reduction in ecosystem services. In intact coastal marine ecosystems, the natural mortality rate of larval fish is often close to 99%, but in the absence of suitable habitats, mortality could reach 100%. In recent decades, conservation activities, management measures, and ecological restoration have been designed and implemented to reduce and compensate for the impacts we have on marine ecosystems (Boissery et al., 2023).

20.4.2 Example of operational ecological marine restoration solutions

Biohut

By using technological innovation, ecological engineering, and ecological restoration approaches, it is possible to enhance and support various ecological processes, leading for example to the diversification of trophic chains or complexification of habitats in targeted aquatic ecosystems.

Ports are often perceived as nature-depleted zones offering few opportunities for life to develop due to habitat homogenization. However, their ecological functions can be enhanced thanks to complex artificial habitats. By providing simultaneously food and shelter to the young fish and crustaceans, microhabitats can enable them to survive and grow during this critical life stage. Among the approaches developed, the Biohut was one of the first artificial habitats to be designed to restore fish nursery functions in shallow habitats (Fig. 20.4). This metallic structure, consisting of a central module filled with a natural substrate (oyster shells) and various protective modules, provides food resources and shelter for juvenile fish, wherever essential nursery functions have been impacted by human infrastructures and activities. Biohut type artificial structure provides a simple but efficient technological solution to mimic structured habitat and ensure the ecological functions of nurseries by providing conditions to limit predation, thus promoting the survival of postlarvae.

After several successive research projects carried out along the French Mediterranean shoreline, led with the support of many scientific partners such as the University of Perpignan and Ifremer (the French National Institute for Ocean Science), the ecological value of the Biohut habitat for juvenile fish in port areas has been strongly validated (Bouchoucha et al., 2016; Mercader et al., 2017, 2018). Biohut is now used as a remediation tool by more than 50 harbors, not only mainly in France but also in Denmark, Nederland, and other non-EU countries.

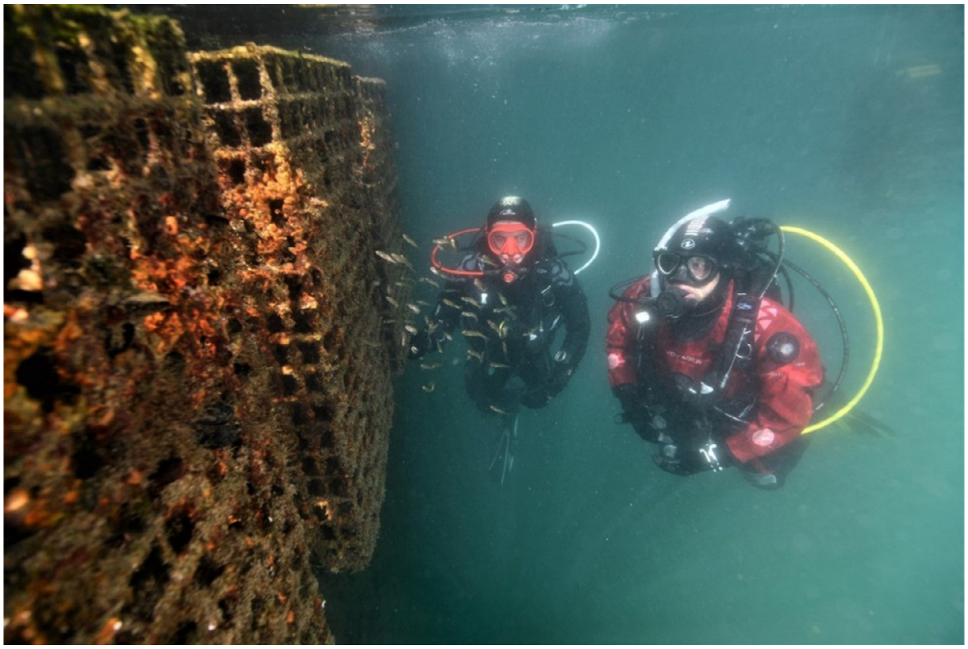

FIG. 20.4 Biohut habitats installed on a dock wall In Marseille (France) to add habitat complexity and protect juvenile fish from predators. *(Photo Rémy Dubas/Ecocean.)*

Continuous monitoring of the artificially structured habitats, performed by scientific divers to assess the species colonizing the artificial structure and their abundance, has allowed to observe more than 100 different fish species and more than 200 different species of invertebrates (crustaceans, mollusks, etc.) (Varenne et al., 2023). The possible reason for this success is probably the food web created within the oyster shells. An artificial structure presents an extraordinary marine biodiversity comparable to a natural zone or even more importantly for some crucial species (e.g., groupers.) (Selfati et al., 2018). Artificial habitats can maximize ecological functions in the short term, while natural zone optimizes them in the long term.

BioRestore, a tool for coastal fisheries enhancement

In the context of fisheries enhancement, some programs breed and release farmed seed as juveniles, but the release of these hatchery-produced animals remains controversial (Bell et al., 2006; Taylor et al., 2017). Despite significant advances in aquaculture techniques, social and economic assessments, ecological modeling, and genetic testing, concerns remain about the potential impacts on wild populations of genetic pollution, homogenization, and the spread of disease (Bell et al., 2006; Lorenzen et al., 2010).

An alternative but understudied approach to the release of farmed juveniles is the harvesting and rearing of wild pelagic postlarvae for release as juveniles (Postlarval Capture, Culture, and Release; PCCR), sometimes termed capture-based enhancement (Bell et al., 2009; Hair et al., 2002). By catching and keeping wild postlarvae until they have reached a size refuge from predation, PCCR-based enhancement aims to mitigate concerns over the negative genetic impacts of releasing cultured hatchery-seed and offers a potentially lower cost, and more genetically diverse source of juveniles better adapted to natural conditions (Bartley and Bell, 2008; Hair et al., 2002).

It consists of capturing fish postlarvae with light-traps in the wild, and rearing them to the juvenile stage in an inland farm until they reach a safe size (7–10 cm) to maximize survival. The juvenile fish can be reintroduced to natural coastal habitats. This process, called BioRestore, aims to enhance the survival rate of postlarvae juvenile fish, because they are captured at a life stage where their mortality rate is still very high, and this rate is reduced to less than 10% (still few mortalities due to disease and other causes) for the period of several months while they are kept in captivity. A recent description of the process is detailed in Richardson et al. (2023) based on a seabream case study in the Mediterranean Sea regarding 4 years of an EU LIFE+ project named SUBLIMO (Life10 Nat/FR/000200).

Coastal fisheries enhancement is already being implemented and has been refined since 2016 in France with two projects (CasCioMar project and Orrea project) to capture and restock fish with enhanced survival rates. Coastal fisheries enhancement is best-suited to coastal species that start life as pelagic larvae before settling to shallow inshore habitats, where they remain site-attached as juveniles and adults, creating self-replenishing populations.

A cost-benefit analysis of the CasCioMar initiative indicated that while long-term impacts are not yet quantifiable, there are net-positive short-term impacts on the fishery, fishers, those directly employed in the supply chain, and regional economic development (CDC Biodiversité, 2019).

In conclusion, as compared to some terrestrial ecosystems, the science and practice of ecological restoration in marine environments, and of its integration within long-term social-economical projects, are still in their infancy. NGOs accompanied by academic scientists are constantly seeking to evolve and improve their tools and the marine portion of the budding restoration sector continues to grow and gain experience.

Wild postlarvae can be successfully captured and cultured, and hatchery-based enhancement programs unequivocally show that organisms can be reared and released cost-effectively and at large-scales, supporting the likely viability of PCCR-based enhancement that combines such approaches (Richardson et al., 2023). Where PCCR can provide income for local coastal communities, it may provide additional socio-economic benefits and promote active stewardship of local marine resources. Indeed, a PCCR initiative could form part of a larger funded initiative designed to restore natural coastal resources and support coastal fishing in a region.

Various adaptations for different contexts have since then been implemented as ecological restoration tools to improve survival rates and food chain recovery for many species of coastal fish and invertebrates. Today, over 5000 systems to help restore and accelerate the reestablishment of nursery functions for juvenile fish are installed in harbors and marinas, offshore substations, canals, floating photovoltaic platforms, and sea outfalls around the world.

It is critical to closely link ecological restoration and engineering interventions with awareness raising and education for local population and institutions, to involve local stakeholders and local communities right from the start of a project. Thus, the impact of restoration actions is not only at the habitat scale, but also reaches the social level, with chances of behavioral changes that can enhance the gains and recovery achieved both by the target ecosystem, the local human communities, and human society as a whole.

In addition, by involving local communities, particularly young people, with dedicated activities, communication actions toward young audiences aim to reach and raise awareness among these future players (Fig. 20.5), to achieve a good level of understanding and involvement in the

FIG. 20.5 Awareness raising activities with children in Agde (France) exploring the organisms settled inside the substrate of a Biohut. *(© Sabrina Palmieri/Ecocean.)*

protection and restoration of biodiversity and the ecosystems near which they live.

20.5 Thinking wide for community effect

The failure of the measures traditionally proposed to mitigate overfishing (reduction of overcapacity, establishment of catch quotas or minimum catch sizes to ensure reproduction, etc.) led, years ago, to the implementation of new "ecosystem approach" management strategies and, in particular, the establishment of marine reserves (Plan Developmental Team, 1990; Roberts and Polunin, 1991; Dugan and Davis, 1993; Agardy, 1994; Pauly et al., 2005; Worm et al., 2009; Pérez-Ruzafa et al., 2017).

Under this perspective, the process of restoring or preventing the deterioration of an ecosystem must be placed in the context of ecological succession and the way in which the system responds to increased stress. Every ecosystem is capable of responding to moderate environmental stress and maintaining its integrity, regulating its main functions and ecological parameters within certain margins of variation through feedback or homeorhetic self-regulation mechanisms, *sensu* Odum (2000). This regulation process usually present more chaotic behavior and pulses and not so much states of equilibrium as those of physiological homeostasis (Odum and Barret, 2006). In this intermediate phase of resistance (Pimm, 1984; Tett et al., 2007), it is difficult to have good indicators of state and to act, because some of the changes are neutralized and those that are observable do not necessarily imply deterioration of the ecosystem, although they may indicate that it is under a certain type of pressure. When stress levels increase, changes become more apparent and can reach a breaking point where ecological integrity collapse catastrophically in Thom's (Thom, 1975) sense. However, at this stage, the system can still recover if the pressures are released. This property is called resilience. Otherwise, a point of no return may be reached that will lead the ecosystem to a state of equilibrium different from the one it had, with different components, relationships, and communities, lower structure and autoregulation capabilities, and dominated by *r*-strategist species that, however, can tolerate higher stress before reaching a new breaking point.

In this framework, beyond recovering populations that have been overexploited by fishing or that have been threatened by direct or indirect human pressure, management measures must be focused from the point of view of restoring the health and ecological integrity of the ecosystem and its historical evolution (SER, 2020). Although there are still gaps to investigate in the mechanisms that operate in marine reserves and the goods and services derived from protection (Marcos et al., 2021), evidence of the positive effects of protection against fishing in no-take areas has been increasing throughout the world during the last two decades (McClanahan and Mangi, 2000; García-Charton et al., 2008; Manel et al., 2019). It has demonstrated the recovery of the natural size and age structure in the populations, the protection of critical spawning stock biomass, the maximization of potential fecundity (Bell, 1983; García-Charton et al., 2004; Claudet et al., 2006), the preservation of genetic diversity and structure of populations (Pérez-Ruzafa et al., 2006), and the reestablishment of ecological interactions (Guidetti, 2006a, 2006b). This led to the conclusion that the populations of directly targeted species were more stable in reserves than in fishing areas, increasing ecological resilience (Babcock et al., 2010). These effects start to be evident in less than 5 years (Halpern and Warner, 2002; Babcock et al., 2010).

This approach is not exempt from ambiguities and problems since ecosystems evolve and present different states throughout the ecological succession, and management decisions are conditioned by human interests. Therefore, the first thing to be fixed in any restoration plan is the objectives to be achieved (Seaman, 2007). However, the great advantage of marine reserves is that they allow for spatial planning that can make the advantages of strict protection (no-take areas) compatible with fishing exploitation regulated by traditional measures within the framework of maintaining the maximum sustainable yield as an upper limit rather than a management target (buffer zones), and with a potential tourist exploitation that can report more economic benefits than fishing activity (Roberts et al., 2003; Roncin et al., 2008; Pérez-Ruzafa et al., 2017).

Therefore, except in cases of extreme deterioration or when the point of no return has been exceeded and it is desired to force the recovery of an ecosystem that has already disappeared, the best available option is to eliminate or minimize the sources of stress and allow the ecosystem to recover its integrity naturally (Pérez-Ruzafa et al., 2018).

An essential aspect for such recovery to be possible, extended in space, and stable over time is the establishment of networks of marine reserves in which connectivity between them is guaranteed (Almany et al., 2009). The flow of individuals across the limits of the reserve not only favors and gives stability to the fishing activity in the adjacent areas, but also guarantees the maintenance of genetic and functional diversity on a large scale in the event of possible mortality events, population imbalances, or alterations forced by more or less catastrophic events. The spatio-temporal scales at which connectivity can be effective is a subject still under discussion.

In the event that human pressures have led to habitat degradation, the loss of structural species (such as corals or seagrass meadows) (Turner et al., 1999), or the appearance of invasive species, the introduction of artificial habitats (Pratt, 1994; Seaman, 2007), the reintroduction of said bioconstruction species (Seaman, 2007), or the elimination of invaders can help recovery, but always bearing in mind that all human intervention involves energy inputs and alterations in the ecosystem that often accelerate degradation processes and may be counterproductive. Although conceptual models and the knowledge of the ecological process involved in ecosystem recovery are consolidated, in practice, the experience of restoring marine and coastal systems is limited and there are few examples of successful recovery (Elliott et al., 2007; Duarte et al., 2015). For this reason, it is essential that all recovery actions include the corresponding scientific follow-up that makes it possible to cover the gaps in knowledge that still persist in this field.

Furthermore, it must be taken into account that anthropogenic impacts have long ceased to have only local consequences and even less in the ocean, in which all the seas are interconnected. Currently, environmental problems are strongly marked by globalization and climate change, which give rise to the mass dispersal of species that become invasive either by human introduction or by shifting their geographic or bathymetric distribution ranges. Therefore, the recovery of ecological integrity cannot be only a strategy of local, regional, or national governments, but rather a joint coordinated planning, including the cooperation between researchers and states, establishing networks of observatories and common data bases to fill gaps in the knowledge of successful practices in recovering ecosystems.

20.6 The need to go further

In recent decades, several tools and methods have been developed in an attempt to restore marine fish habitats and populations. One of the main obstacles to the more extensive use of restoration tools has been the lack of means to assess the effectiveness of measures. Significant progress has been made in this direction, and today effectiveness assessment is considered from the outset of restoration projects to better measure their effects. Several trials of seagrass habitat restoration using seed planting techniques suggest that this technique could be used to restore areas of several hectares in size (Seagrass restoration initiative, Wadden Sea), thereby restoring essential habitats for a wide variety of species. The use of artificial reefs or artificial structures to recreate habitats for very young fish stages where these habitats have been damaged (harbor areas, marinas), combined with the capture and larval rearing of several species, seems promising, as these techniques can limit natural mortality to support biodiversity. The aim is not to repopulate the seas in this way, but simply to reduce the impact of coastal developments on certain species. The use of shellfish reefs, and in particular wild oysters, has been commonplace in the United States for almost 50 years and appears to be gaining popularity throughout the world, including Australia, New Zealand, China, India, and Europe on the shores of the North Sea and the English Channel. The technique works well and has the advantage of offering additional ecosystem services by protecting the coastline from erosion and reducing wave energy. In the context of current climate change and sea level rise, the addition of ecosystem services to those expected from fish habitat restoration is a good thing. However, the effects of climate change are still too rarely taken into account in studies related to fish habitat restoration. The effects of ocean acidification, rising temperatures, and sea level rise are all parameters that can have an impact on the success of restoration actions. Therefore, before any action is taken to support stocks or restore degraded habitats, whatever the means used, it is essential to assess not only current environmental conditions but also how these conditions are likely to evolve, to maximize the chances of success. Expected advances in environmental DNA research, and in particular, quantitative estimates, will certainly make it possible to better assess the effects of fish population restoration in the future. However, it should be stressed that even if restoration is possible, it is still better not to need it.

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