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Fish-smart seawalls: a decision tool for adaptive management of marine infrastructure

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Fish-smart marine infrastructure

Infrastructure is increasingly being built in marine habitats, with extensive ecological consequences for benthic and fish assemblages alike. The practice of ecological engineering attempts to mitigate the negative impacts of infrastructure through the design of artificial structures that benefit both humans and nature. Although research has primarily focused on the benefits for invertebrates and algae, fish also respond to changes in habitat complexity and benthic biodiversity. We surveyed the scientific literature on natural and artificial reefs to identify key habitat features that fish respond to, and propose a decision tool for ecologists and managers to tailor the structural complexity of marine infrastructure for fish. Inevitably, natural habitats will increasingly be replaced with artificial ones, making ecologically sensitive designs essential for maintaining biodiversity and ecosystem services. Using lessons from natural and artificial reefs, we show that existing and new infrastructure could be

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designed not only to reduce negative impacts but also to foster positive effects on fish assemblages.

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In a nutshell:

- Ecological engineering can mitigate the negative impacts of built infrastructure on marine assemblages
- Fishes are known to respond to certain habitat features on both natural and artificial reefs
- Knowledge gained from the association of fish with natural and artificial habitat features can be applied in marine management to create “fish friendly” infrastructure (ie that enhances local diversity and productivity of fishes)

Coastal urbanization affects marine systems through the construction of artificial infrastructure. More than 50% of foreshores in selected estuaries worldwide are defended with hard engineering, such as seawalls and breakwaters (eg in the US and Australia; Figure 1a; Dugan *et al.* 2011;), but infrastructure inserted into marine ecosystems is not limited to coastal armoring; other examples include structures intended for commercial, residential, or recreational purposes (eg marinas, pilings, pontoons, swimming enclosures, airports, “canal estates”), offshore energy installations (eg oil rigs, wind farms), and fishery-based features (eg aquaculture farms, fish aggregation devices) (Dafforn *et al.* 2015b). In addition, the deployment of artificial reefs is used in marine management and tourism worldwide as a tool to enhance commercial fisheries, provide sites for recreational diving and snorkeling, and mitigate impacts to natural reef habitat (reviewed in Baine 2001; Feary *et al.* 2011). Although artificial reefs can be considered to be a human construct in the marine environment (Feary *et al.* 2011; Dafforn *et al.* 2015b), they differ from other marine infrastructure in that these reefs are purposely designed for ecological effects, whereas in general, marine infrastructure is engineered primarily for socioeconomic purposes. The scientific literature on how fish assemblages are influenced by artificial reefs is extensive, but little research has been conducted on how they are influenced by marine infrastructure. Here, we consider marine infrastructure separately from artificial reefs.

Coastal urban sprawl often drives the loss of important coastal and marine habitats and the addition of hard substrata for colonization by reef species (Bulleri and Chapman

2010). Despite an increasing amount of research demonstrating the substantial ecological impacts of these artificial structures (see Bulleri and Chapman [2010] for a review), coastlines continue to be altered with few changes in practices to manage such impacts. Moreover, construction of marine infrastructure is likely to expand in the future due to climate change, which will require improved defenses for coastal cities against sea-level rise and more frequent and intense storm events (IPCC 2014). “Ecological engineering” or “eco-engineering” is the attempt to redesign built infrastructure to be multifunctional, benefiting both humans and nature (Chapman and Underwood 2011; Dafforn *et al.* 2015a). For instance, the addition of complex surfaces and novel habitats to infrastructure can contribute to the rehabilitation of species living on these structures (reviewed by Dafforn *et al.* 2015a). To date, eco-engineering research has been primarily directed toward enhancing benthic diversity. However, increased benthic diversity and habitat structural complexity (hereafter, “habitat or structural complexity”) added through eco-engineering has recently been shown to influence fish assemblages associated with artificial habitats (Toft *et al.* 2013; Sella and Perkol-Finkel 2015; Morris *et al.* 2017a). In this paper, we first review the consequences of marine infrastructure for fish. By using examples from investigations on natural reefs and artificial reef design, we then propose a decision tool to guide management and future research in eco-engineering toward not only reducing negative impacts, but also fostering benefits of existing and new artificial structures for fish populations.

Consequences of marine infrastructure for fish assemblages

Much of the literature on fish and marine infrastructure has documented patterns, numbers and/or abundance of fish species around infrastructure, and made comparisons between adjacent habitats or natural hard substrata (WebTable 1). Coastal (eg breakwaters) and offshore (eg oil rigs) infrastructure has been colonized by diverse fish assemblages (Figure 1c; Rilov and Benayahu 1998), including species of commercial value (Pradella *et al.* 2014) and those that are in decline in their natural habitat (Love *et al.* 2006). Marine infrastructure is often built on soft sediments, and in comparison with the adjacent soft substrata or open water, a localized increase in fish biodiversity can occur in response to the construction of some types of infrastructure (Guidetti 2004). However, increases in fish diversity are typically restricted to species associated with the newly created reef rather than among the pre-existing soft-bottom assemblage. The creation of hard infrastructure in the marine environment often comes at the loss of soft-bottom habitat and its associated fish assemblage (Heery *et al.* 2017). Similarly, replacing saltmarsh habitat with coastal armoring can have

negative impacts on the early-life stages of fish (Peterson *et al.* 2000) and potentially affect connectivity between habitats (Bishop *et al.* 2017). For instance, artificial structures can facilitate the expansion of invasive benthic species, including tunicates (Airoldi *et al.* 2015) and fishes (eg lionfish [*Pterois* spp]; Smith and Shurin 2010) by providing habitat for colonization. Furthermore, the presence of piers along shorelines has consistently been shown to have negative impacts on the number of fish species, as well as on fish abundance, behavior, and growth. This is likely due to the creation of intensely dark environments, which can reduce prey availability, impair visual-based behaviors, and constrain movement (Munsch *et al.* 2017). Marine infrastructure can be dominated by a few groups of fish (eg Rilov and Benayahu 1998) and often does not have the same assemblage of fishes in comparison to natural reefs (eg Burt *et al.* 2009). Therefore, such infrastructure should not be considered a surrogate for natural reefs.

As with artificial reefs, the degree to which marine infrastructure contributes to the production of fish biomass remains a topic of debate (Bohnsack 1989; Macreadie *et al.* 2011). For example, at small spatial extents, increased densities of fish were observed aggregated near individual offshore wind turbines, whereas no effects on fish abundance were seen at larger spatial extents when comparing areas with wind turbines to reference sites without turbines (Bergstrom *et al.* 2013). If hard-bottomed habitat is not a limiting factor for fish, then adding artificial structures may only result in the attraction and aggregation of fish (the “attraction hypothesis”; Bohnsack 1989). This can exacerbate sustainability problems in already overexploited fisheries by causing fish to be more easily caught (Bohnsack 1989) or if individual performance (growth and reproduction) is lower on the artificial structure than on accessible natural reefs, although this may not always be the case (Smith *et al.* 2015). Unlike attraction of fish, production of fish is difficult to quantify and requires long-term monitoring of populations over sufficient spatial and temporal scales (Macreadie *et al.* 2011). Offshore oil rigs in California are considered to support high levels of fish productivity, primarily due to the recruitment and subsequent growth of rockfish species, and therefore provide evidence for the fish production rather than the attraction hypothesis (Love *et al.* 2007).

Eco-engineering to mitigate negative impacts of marine infrastructure

Termed “reconciliation ecology” (Rosenzweig 2003), the ecologically sensitive design of built infrastructure is not a new concept, but it has received comparatively little attention in marine as opposed to terrestrial systems. Eco-engineering research in the marine environment

has been primarily directed toward developing benefits for benthic invertebrate and/or algal diversity through additive (attachment of protruding structures that are either abiotic or biotic) or subtractive (drilling or removal of substrata) methods to increase surface area and/or habitat complexity (Figure 1, b and d; Strain *et al.* 2017b). However, there is a knowledge gap regarding the effects of eco-engineered marine infrastructure on non-sessile species, such as fish.

A small number of studies have demonstrated that increased benthic diversity and structural complexity provided by eco-engineered habitats can increase the number of species and abundance of fish associated with marine infrastructure (Panel 1; Toft *et al.* 2013; Sella and Perkol-Finkel 2015; Strain *et al.* 2017a). This benefit does not seem to accrue if complexity features derive from the presence of additional soft structures (eg coir turf, a natural coconut fiber matting), as these had no effect on visiting fish assemblages (Morris *et al.* 2017b). Similarly, the addition of complexity through the incorporation of holes in the foundations of wind turbines did not have an effect on fish abundance, which may suggest a species-specific response (Langhamer and Wilhelmsson 2009).

Few studies have examined the particular influence of features of marine infrastructure on local fish populations. Greater topographical complexity and cover of complex epibiota has, however, been found to have a positive effect on the number of species and abundance of fish around marine infrastructure (Rilov and Benayahu 1998; Clynick *et al.* 2007). Love and York (2006) identified a positive relationship between the response of fish species that typically associate with natural rocky outcrops and the amount of bottom horizontal beam exposed to the sediment at oil platforms, concluding that sheltering habitat was an important feature of man-made reefs. The vertical relief of infrastructure may also influence fish recruitment, with greater recruitment occurring on structures that span the entire water column (Rilov and Benayahu 1998). Despite the lack of research focusing on the effects of marine infrastructure on fish assemblages, the design of multipurpose marine infrastructure for fish may be informed by existing observational and manipulative studies at natural and purposely designed artificial reefs.

Lessons learned from natural reefs

In marine systems, environmental variables that influence fish assemblages differ at large (beyond hundreds of meters) and small (<100 m) spatial extents. For instance, at large spatial extents, fish populations are strongly related to depth and habitat type, with distinct communities occurring at different depths and habitats (Hamilton *et al.* 2010; Fitzpatrick *et*

al. 2012). At smaller spatial extents – within a reef patch, for instance – fish assemblages are affected by variables such as habitat complexity (Harborne *et al.* 2012), and benthic cover and diversity (Harborne *et al.* 2011). In general, individual instances of marine infrastructure cannot modify the marine environment over large spatial extents, with the exception of adding habitat that contributes to the spatial structure of marine metapopulations (ie a group of populations of a species separated by space but connected by dispersal). Thus, here we will focus on the environmental features that operate over small spatial extents and that can be easily manipulated when constructing artificial structures to influence fish assemblages.

Structural complexity is the physical three-dimensional structure of a habitat, and it provides a variety of resources to organisms in marine ecosystems (see review by Graham and Nash 2013). Structural complexity affects fish assemblages and community composition by providing refuge and physical habitat for benthic communities, providing fish with both primary and secondary resources, such as food and shelter from both biological (eg predators) and environmental (eg wave exposure) stressors (Harborne *et al.* 2011). Fish behavior, and therefore key ecological processes, are also affected by structural complexity; for example, some herbivores and planktivores prefer less complex areas where they can forage while simultaneously monitoring their surroundings for threats (Rilov *et al.* 2007), although some species may forage within more structurally complex habitats when predation risk is high (Holbrook and Schmitt 1988). The relationship between fish abundance and structural complexity may be influenced by many factors, including body size, home range, fine-scale mobility, trophic preference, and life-history traits (Bozec *et al.* 2013). Benthic and fish diversity can be enhanced through the contribution of structural complexity to habitat diversity and resource partitioning (Risk 1972). Structural complexity is one of the most important environmental variables affecting fish across small spatial extents, and is therefore a critical factor to consider in the design of marine infrastructure.

Numerous measureable components of structural complexity have been described, the ecological importance of which are well understood in some cases. For instance, features of natural reefs that have a relationship with associated fish assemblages include the density and size of shelters; vertical relief; and the rugosity index (a measure of substratum complexity, *sensu* Risk 1972) (WebTable 2; eg Gratwicke and Speight 2005); likewise, there is a positive relationship between shelter density/size and fish density/size on coral reefs, with larger shelters supporting larger and disproportionately more fish (Menard *et al.* 2012). On temperate reefs, structural complexity is often created or enhanced by macroalgal growth, and this biotic structure can interact with the abiotic topography of the reef to affect the fish

assemblage. For example, the positive relationship between large-bodied fish and macroalgal stipe density (the stipe is a stem-like algal structure) on temperate rocky reefs was weakened by increasing reef rugosity, thereby altering the size-structure of the fish assemblages (Trebilco *et al.* 2015). Regardless of its source (abiotic or biotic), structural complexity can influence fish in both positive and negative directions, and different functional groups are affected to different extents by complexity (Rilov *et al.* 2007).

Structural complexity is directly related to benthic assemblage composition (eg Ferrari *et al.* 2016), which in turn determines fish diversity and abundance (Harborne *et al.* 2011, 2012). For instance, the number of fish species was positively correlated with the number of benthic growth forms in different habitats in the Caribbean, whereas height of the habitat was important for fish abundance (Gratwicke and Speight 2005). In particular, habitat structures that are at least 50 cm in height are strongly related to high abundance of reef-associated fish across different habitats and depth gradients (Harborne *et al.* 2012). In temperate reefs, where macroalgae provide important physical structure, fish species richness, diversity, and abundance, along with recruitment of many species, are all positively related to the density (Fobert and Swearer 2017) and height (Levin and Hay 1996) of macroalgal stipes, as well as to the composition of the algal canopy (Cheminée *et al.* 2013).

Structures that provide shade have also been linked to fish abundance and diversity; this relationship is positive in shallow tropical reefs due to protection from solar irradiance (Kerry and Bellwood 2015), but can be negative in some temperate systems (eg under piers, as described above; Munsch *et al.* 2017), highlighting the importance of considering the context (eg tropical versus temperate; shallow water versus deep water) when designing artificial structures for fish assemblages. To summarize, properties such as topographical complexity, benthic diversity, presence and size of shelters, and vertical relief have major effects on fish in natural systems (Table 1), and are all aspects that have the potential to be modified when designing marine infrastructure. Given that different groups can be positively or negatively affected by particular properties, management goals should be defined at the start of a project (see below).

Although we have identified structural complexity as a dominant factor that influences fish assemblages, the value of marine infrastructure for fish will also depend on the seascape composition, as in natural systems. For instance, because many fish display habitat shifts with age, it is necessary to maintain connectivity between the habitats required at different life stages (Fitzpatrick *et al.* 2012). Changes in environmental gradients due to factors such as depth and wave exposure also promote differences in fish assemblages

(Fitzpatrick *et al.* 2012; Borland *et al.* 2017). Thus, the context in which the infrastructure is placed needs to be considered, and will also determine the targets that can be achieved.

Lessons learned from artificial reefs

Research on natural reefs is generally limited to correlative studies between fish and habitat features, due to the difficulty in manipulating natural substrata (but see Cheminée *et al.* 2013). In contrast, artificial reefs can be easily manipulated at the design stage, and this can be useful in determining causation between habitat features and effects on fish assemblages. Design is a major theme in the artificial reef literature, and can include a variety of attributes such as material used, substratum complexity, vertical relief, size, and spatial configuration (WebTable 2; Baine 2001). There are several aspects of a custom-built artificial reef that could be manipulated and, in theory, influence local fish assemblages (Table 1). The above aspects are of particular interest in this review, because they could easily be controlled when materials are deployed, and are equally applicable to the design of marine infrastructure.

One of the most thoroughly studied aspects of artificial reef design is the effect of interstitial spaces. Interstices (the spaces, gaps, or holes in or between substrata) can be important drivers of local fish assemblages by providing shelter (Sherman *et al.* 1999). Reef units that had no gaps had fewer fish species and lower fish abundance (Kellison and Sedberry 1998), with the number of fish increasing with the number of gaps provided (Gascon and Miller 1982). Conversely, some studies, including a recent meta-analysis (Strain *et al.* 2017b), have indicated that reef holes have no effect on species richness, which suggests that the use of holes needs to be considered on a site-specific basis (WebTable 2; Strain *et al.* 2017b). However, the effect of interstice may be more prevalent when different groups within the assemblage are studied. Some studies have confirmed that the number of species, as well as the abundance and size of fish, differ when larger or smaller shelters are used. For example, Hixon and Beets (1989) concluded that fish size corresponded with refuge size (ie bigger fishes used larger holes), while other studies have demonstrated no difference between treatments using different-sized interstices (Sherman *et al.* 1999). The effect of interstitial spaces can be complicated by trophic interactions, with shelters for small fish becoming more important where there are higher numbers of predators (Gascon and Miller 1982; Hixon and Beets 1989). Consideration of ecological interactions is therefore also important when designing marine infrastructure, particularly if there are species-specific management objectives.

In addition to interstitial spaces, other topographical aspects, such as vertical relief, can affect the associated fish assemblages directly (eg recruitment; Wilhelmsson *et al.* 2006) and/or indirectly (eg benthic assemblage; Bulleri and Chapman 2010). For instance, one of the largest artificial reef experiments, which was conducted on reefs adjacent to the San Onofre Nuclear Generating Station in southern California, tested the relative effectiveness of several aspects of reef design on fish assemblages. This study found that characteristics contributing to the physical footprint of the reef (ie the amount of bottom covered by hard substrate) had a substantially positive influence on the density, richness, and biomass of the fish assemblage, as well as on young-of-year recruitment, whereas the same metrics were relatively insensitive to material type (quarry rock or recycled concrete rubble) (Reed *et al.* 2006). However, research elsewhere has indicated material type to be of importance, with the number of some species of fish and their abundance differing between reefs made of different materials (eg tires, wood, metal, sandstone; Chapman and Clynick 2006). The addition of hard floating structures (eg fish aggregating devices; Kellison and Sedberry 1998) to reefs can also increase the diversity and abundance of fish. Furthermore, high-relief structures are known to improve recruitment (Rilov and Benayahu 2002) and support greater numbers of planktivores, possibly due to the creation of favorable flow patterns (Wilhelmsson *et al.* 2006). A common practice among artificial reef studies is to compare the fish assemblage to that on nearby natural reefs. An important and intuitive trend here is that where the topography of artificial reefs is similar to that of adjacent natural reefs (low relief, low rugosity, and composed of small- to medium-sized boulders), local fish assemblages also tend to be similar (Granneman and Steele 2015).

Spatial layout and reef size are additional drivers of fish assemblages; abundance and diversity (per unit of habitat) appear to increase with more numerous, smaller reefs (Bohnsack *et al.* 1994). Isolated reefs have also been shown to have greater diversity and biomass per unit area (Belmaker *et al.* 2005). Larger reefs, on the other hand, tend to support larger individual fishes (Bohnsack *et al.* 1994). The layout of a reef or piece of infrastructure will also have implications for species associated with ecotone habitats (Bellquist *et al.* 2008). These trade-offs reinforce the importance of framing infrastructure works in the context of specific ecological objectives.

Application to the management of marine infrastructure

This review has summarized a broad range of information useful for “fish friendly” design of marine infrastructure from studies of both natural and artificial reefs (see Table 1 for a

summary). Generally speaking, the effects of different habitat features on fish were consistent across natural and artificial habitats, which is beneficial for the application of this information to marine infrastructure. The only parameter where the literature from natural and artificial reefs disagreed was the effect of diversity of abiotic/biotic structures on species richness, which was positive for natural reefs but had no effect for artificial reefs (Table 1). Although there was a trend toward increasing fish species richness with diversity of benthic growth forms at artificial reefs, this trend was not statistically significant (WebTable 2).

There was a lack of information regarding some features of artificial or natural habitats (Table 1). In particular, data were focused on species richness and abundance of the fish assemblages, with fewer parameters tested for specific groups of fish (eg at a particular trophic level). If the management objective is more specific than simply increasing fish diversity generally, then there is less certainty about aspects of habitat design that will target certain groups (WebFigure 1, pink boxes). Targeting functional groups of fish may be desirable, as research has shown that enhancing functional rather than taxonomic diversity can increase the ecosystem services and productivity of assemblages (Stuart-Smith *et al.* 2013). Furthermore, in some cases, contrasting information was found within either artificial or natural reefs. This suggests that management initiatives may be context dependent (Chapman and Underwood 2011), and highlights the importance of evaluating projects on a case-by-case basis.

The successful application of this information in future projects will have, at its core, the early and specific identification of the desired properties of the fish assemblage at the structure (WebFigure 1, diamonds). On the basis of our literature review, we propose that common objectives for enhancement include fish biodiversity generally, specific fish groups, or even a particular fish species. For each target, there are general categories of ecological considerations that should be included in decision making; for instance, when targeting a particular fish species, one needs to identify whether one or more life stages are targeted (eg nursery habitat, spawning habitat) and the resources required at each life stage (WebFigure 1, yellow boxes). The ecological bases for these resources need to be known in order for them to be enhanced (see Panel 2 for an example). In all cases, the availability of required supporting habitats must be evaluated, and if they are unavailable, flexibility in the location of the structure will have to be considered (WebFigure 1, yellow and purple boxes). If there is flexibility with regard to the location, structures could be positioned relative to natural/artificial reefs and other supporting habitats (eg salt marsh, sedimentary habitats) or along varying environmental gradients to promote greater diversity of species (WebFigure 1,

purple boxes). One should also consider the variety and abundance of structural features needed to achieve the targeted objectives (Table 1; WebFigure 1, blue and pink boxes).

Once the biological target or targets have been identified, it is then necessary to assess the structural requirements against the design limitations (engineering, financial, political, social) of the project. For instance, if the project involves coastal armoring, what level of slope is possible? Must the structure be one contiguous piece? How large or small can holes be (if any are possible) without interfering with its functional role? What is the additional financial cost (if any) of changing the design of the structure, and is this within budget? Given that artificial structures are human-driven insertions into the environment, their social value has been a target for recent research (Morris *et al.* 2016) due to the importance of public support for the success of eco-engineering projects. A public consultation may be a required step prior to eco-engineering projects. Once limitations have been identified, it is necessary to review and possibly revise the biological targets in light of these limitations, an important iterative step in which the expectation for the resulting fish assemblage and design of the structure must be revised so they are complementary. This is the time for creativity and synergies, where ecological requirements can be viewed as opportunities for innovation. Many projects seek to satisfy specific biological or ecological requirements by creating novel artistic or architectural features that can, for example, provide increased structural complexity on seawalls or even control the amount of shading under wharfs through the use of transparent or opaque ground panels, depending on desired outcomes (as in the juvenile salmon eco-engineering case study described in Panel 1).

The final component for the successful application of “fish friendly” design to marine infrastructure is ongoing monitoring and adaptive management (WebFigure 1, red box). It is critical that the original ecological objectives of the project are assessed and, where possible, adaptive management options and trigger points incorporated into the design. For instance, it may be possible to change the design of panels of differing complexity that have been retrofitted onto artificial structures if monitoring data suggest that the original objectives are not being met. The combination of monitoring and adaptive management will not only enhance the probability of success of individual projects but can also inform other projects.

Conclusions

While much research has focused on the effects of habitat features on fish assemblages in natural and artificial reefs, relatively little is known about the association of fish with marine infrastructure. Aligning with previous guidance for eco-engineering targeted at benthic

organisms, we have identified key habitat features that are important for fish and proposed a decision tool for incorporating these features into marine infrastructure to manage fish populations.

Our goal was to capture aspects of complexity that can be used directly to inform management. Although manipulation of habitat complexity is likely to have an impact on fish assemblages, there is a major knowledge gap regarding the fitness consequences for fish associated with artificial structures. The impacts of eco-engineering on metapopulations are unknown, as is the scale of enhancement needed to provide any measurable difference in fish populations. This has been a contested subject in the artificial reef literature for many years (Bohnsack 1989), and is an important consideration in cases where marine infrastructure represents a large portion of available habitat for a species within a particular area.

Nevertheless, applied research to measure and construct aspects of complexity is likely to be invaluable in the management of current and future marine infrastructure. Moreover, successful implementation of physical structures to support targeted ecological impacts for fish communities could contribute substantially to a large number of policy objectives worldwide, in particular the promotion of sustainable development and maintenance/rehabilitation of biodiversity and ecosystem functioning (Dafforn *et al.* 2015b). Interdisciplinary collaboration between scientists, managers, engineers, and other stakeholders will provide the opportunity to fill existing knowledge gaps.

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Supporting Information

Additional, web-only material may be found in the online version of this article at

Figure 1. Selected examples of marine infrastructure. (a) Seawalls protect shorelines; (b) water-retaining “flowerpots” increase the biodiversity of seawalls; (c) fish associated with oil rigs; and (d) eco-engineered tiles seeded with oysters.

Image credit:

(c) © rig2reefexploration.org

Figure 2. Eco-engineered seawall in Seattle, Washington. (a) Designed for juvenile salmon, the seawall includes (1) skylights to increase light penetration below the sidewalk, (2) complex walls to benefit greater numbers of invertebrate prey, and (3) marine mattresses to create a shallower migratory corridor. (b) View of the skylights from the sidewalk above.

Image credits:

(a) © U Washington

(b) © U Washington

Figure 3. Example of how marine infrastructure can be designed to benefit the commercially important yellowfin bream (*Acanthopagrus australis*) and yellowtail scad (*Trachurus novaezelandiae*) fisheries. Seagrass meadows (A) are facilitated in protected areas such as the leeward side of breakwaters. Seagrass and mangrove (B) rehabilitation can promote juvenile bream (C) forage and shelter. Connectivity with estuarine habitat could be facilitated by building patch reefs (D) in open areas between the structure and nearby estuaries. Breakwater units have small-scale complexity (E) to support prey items (F) and reefs are deployed in areas adjacent to soft sediments (G), thus increasing transition zones, habitat for yellowtail scad (H), and foraging areas for bream (I). Objects of high vertical relief are built offshore of the structure to provide habitat and food (J) for juvenile scad (K). Symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (www.ian.umces.edu/symbols).

Panel 1. Fish-smart seawalls: a case study

Research in Seattle, Washington, presents one of the largest-scale eco-engineering projects for a target species of fish worldwide. The juveniles of threatened Pacific salmon species use the shoreline as a migratory corridor, and the need for a seawall upgrade provided an opportunity to enhance the habitat for juvenile fish and the invertebrates on which they feed (Figure 2; Munsch *et al.* 2017). Trials in the first stage of the project showed that more complex habitat enhancement panels, which incorporated steps and fins (protruding ledges at various angles), substantially increased the density of epibenthic prey species for juvenile salmon as compared to prey densities on flat tiles (Goff 2010). Replacing seawalls and riprap with two shoreline types (pocket beach and habitat bench) that created nearshore shallow areas also promoted greater densities of invertebrate prey and juvenile fish as well as incidence of fish feeding behavior (Toft *et al.* 2013). A pilot study also suggested that light-penetrating panels facilitated greater use of areas under piers by juvenile salmon (Cordell *et al.* 2017). The seawall is still under construction; a 10-year monitoring program will be implemented following its completion.

[SPS – please embed Figure 2 in Panel 1]

Panel 2. How fishery species-specific habitat elements can be incorporated into the design of marine infrastructure

In this example, the structure is tailored toward two important fishery species: yellowfin bream (*Acanthopagrus australis*) and yellowtail scad (*Trachurus novaezelandiae*). Yellowfin bream is an estuarine and coastal species relying on seagrass and mangroves for juvenile stages, with adults commonly found over soft sediments near rocky reefs or over seagrass, where they forage for small fish, crabs, prawns, and worms (Kalatzis and Baker 2010). Yellowtail scad is a planktivorous, schooling, coastal pelagic species; adults are associated with rocky reefs and juveniles are often found at high vertical relief structures like wharves and over soft sediments (Rowling *et al.* 2010). By incorporating this knowledge into the design process, appropriate habitat elements can be included in the final structure (Figure 3). The modifications listed in Figure 3 are likely to have substantial benefits for bream, scad, and other groups as well. Where a feature is likely to have positive impacts for one group but negative impacts for another, managers will need to make decisions based on their own priorities.

[SPS – please embed Figure 3 in Panel 2]

Table 1. Summary of the effects of the physical properties of artificial and natural reefs on fish assemblage measures

Increasing the physical properties listed below has resulted in:	Information is for the abundance of trophic/size groups:															
	Biomass		Abundance		Sp richness		Planktivores		Herbivores		Predators		Large fish		Recruitment	
	A	N	A	N	A	N	A	N	A	N	A	N	A	N	A	N
Reef or habitat patch area	+/-	+	+/-	+	+	+/=							+		=/-	
Edge/area ratio			+		+								-		-	
Inter-reef space	+		+		+	-			=		+/-		+/-		+	
Complexity (rugosity)	+	+	+/=	+/=	+					+/-			-		+	
Vertical relief ^a		+	+/=	+	+/=	+	+			+/-	+		+			+
Density of vertical structures		+		+		+	+			+/-	+		+		+	+
Density of holes	+	+	+	+	+/=								+			
Diversity of hole size			=		=											
“Small” holes			+		+											
“Large” holes	+	+	+	+	+								+		-	
Size of overhangs		+		+		+	+			+/-	+		+			
Density of structures ^b	+	+	+	+/-		+/=	-			+/-/=	+/=				+	+/-
Diversity of structures ^b	+		+	+	=	+										

Notes: Artificial (A) and natural (N) reefs. Positive effect [+], negative effect [-], no effect [=]. Blank cells indicate no information was found. Symbols in combination indicate where different studies produced inconsistent results. For literature included, refer to WebTable 2. ^aCommonly referred to as “tall structures” in the natural reef literature. ^bRefers to both abiotic and biotic structures.

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