Effects of shoreline armouring and overwater structures on coastal and estuarine fish: opportunities for habitat improvement

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Summary

1. Nearshore ecosystems are increasingly recognized as critical habitats for fish of cultural, ecological and economic significance. These ecosystems are often densely inhabited by juvenile fish, highly productive and refuges from predation, leading ecologists to characterize them as nurseries. However, nearshore ecosystems are being transformed globally to support demands of growing coastal populations. Many shorelines are modified by armouring (e.g. seawalls, riprap) that minimizes erosion, and overwater structures (e.g. piers, docks) that facilitate waterfront use. These modifications affect the ecology of nearshore systems by restructuring, eliminating and shading shallow waters.

2. Here, we review literature examining effects of armouring and overwater structures on coastal and estuarine fishes, and discuss how research and management can coordinate to minimize negative effects.

3. Along armoured shorelines, fish assemblages differed from unarmoured sites, fish consumed less epibenthic and terrestrial prey, beach spawning was less successful and fish were larger. Under large overwater structures, visually oriented fish were less abundant and they fed less. Shade from overwater structures also interrupted localized movements of migratory fish. Thus, shoreline modifications impaired habitats by limiting feeding, reproduction, ontogenetic habitat shifts from shallow to deeper waters and connectivity.

4. Research suggests that restoring shallow waters and substrate complexity, and minimizing shading underneath overwater structures, can rehabilitate habitats compromised by shoreline modifications.

5. Synthesis and applications. Shoreline armouring and overwater structures often compromise fish habitats. These threats to nearshore fish habitats will become more severe as growing coastal populations and rising sea levels increase demands for shoreline infrastructure. Our ability to assess and rehabilitate nearshore fish habitats along modified shorelines will be enhanced by: focusing research attention on metrics that directly indicate fish habitat quality; implementing and evaluating shoreline features that repair compromised habitat functions within human-use constraints; collating natural history knowledge of nearshore ecosystems; and embracing the socio-ecological nature of habitat improvements by educating the public about conservation efforts and fostering appreciation of local nearshore ecosystems. Actions to reduce impacts of shoreline modifications on fish are particularly feasible when they align with societal goals, such as improving flood protection and providing spaces that facilitate recreation, education, and connections between people and nature.

Key-words: coastal squeeze, fish nurseries, habitat evaluation, nearshore ecology, overwater structures, piers, riprap, seawalls, shoreline armouring, urban planning

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Introduction

People have modified waterfronts for millennia. Ancient Alexandria, founded 331 BCE, was a prototype for the modern port city: its engineers built harbours featuring wharves and brick seawalls that allowed ships to support the largest trade centre in the world (Schwartz 1980; Lawler 2005). Shoreline infrastructure dates at least to 2300 BCE, when people created docks in present-day India by excavating and lining basins with bricks (Rao 1973). Waterfront civilizations have long prospered from aquatic resources and trade, and are now major components of the global economy, supporting not only international trade but also a diversity of local industries such as tourism and real estate. Currently, 44% of all people live within 150 km of shore and many of the world’s largest cities are on the coast (Ross 1995; Small & Cohen 2004).

People have introduced waterfront infrastructure throughout the world. Shorelines are often modified by armouring (e.g. 14% of USA; Gittman et al. 2015), the replacement or shielding of natural shoreline substrates with hard and resistant materials to minimize erosion and protect infrastructure (e.g. seawalls, riprap) (Bulleri & Chapman 2010), and overwater structures that facilitate water access (e.g. piers, docks) (Fig. 1). Armouring restructures aquatic-terrestrial ecotones and can create deep waters next to shore when built in intertidal zones. Overwater structures, particularly those that are large, close to water levels, and supported by many piling, can create dark environments and high-contrast shadow edges. Widespread modification to shorelines is concerning because estuaries and coasts provide ecosystem services (e.g. cultural resources, food, flood protection, recreation) worth tens of trillions of US dollars annually (Costanza et al. 1997; Temmerman et al. 2013). Fish are an important component of these services, as many shallow ecosystems are thought to provide nurseries for fish of cultural, ecological and economic significance.

Nearshore ecosystems and their fish habitats warrant protection, but their management is complex. Fish are mobile and not easily observed, and evaluating fish habitats requires us to understand the benefits of habitat features, functions and processes. Furthermore, many shorelines are extensively modified, centuries removed from natural conditions, and their restoration outcomes are uncertain. Economic or social pressures may disincentivize restoration, and shoreline ecosystems may be managed more pragmatically as novel socio-ecological systems (Hobbs et al. 2014; Miller & Bestelmeyer 2016). Research attention has recently focused on effects of shoreline modifications on fish, and how to rehabilitate impaired habitat functions. In addition, the US Government is initiating policies that require that ecosystem goods and services are accounted for in federal decision-making (White House 2015). Thus, it is timely to consider how we can build waterfronts that promote functional fish habitats and benefit society.

Here we review literature examining effects of shoreline armouring and overwater structures on estuarine and coastal fish, and suggest how research and management can minimize negative effects in relation to constraints and opportunities for human use. In this review, we use the term ‘management’ to refer to decisions that address disturbances caused by shoreline modifications and thereby change ecological function. We conducted a comprehensive review of studies that (i) compared fish ecology among shorelines that were (a) modified by armouring or overwater structures, (b) unmodified, or (c) modified by unconventional infrastructure designed to improve habitat, (ii) occurred directly along the shoreline (e.g. excluding offshore breakwaters, subtidal artificial reefs) and (iii)
occurred along estuaries or coasts. We identified a focal literature by collating studies that met these criteria from the first 400 results of separate Google Scholar searches for the following terms: ‘fish shoreline armouring,’ ‘fish shoreline bulkhead,’ ‘fish shoreline riprap,’ ‘fish shoreline seawall,’ ‘fish shoreline dock,’ ‘fish shoreline “overwater structure’” and ‘fish shoreline pier,’ selecting from 2800 total search results, albeit with substantial repetition in papers returned among searches. We also incorporated one article that was not yet detectable by Google Scholar (Cordell et al. 2017). To contextualize fish responses, we referred to studies not identified in the search that described basic nearshore ecology and effects of shoreline modifications on non-fish taxa. We also occasionally drew from related freshwater studies for subject matter that was lacking in our focal literature. Overall, we attempted a thorough review of fish responses to shoreline modifications along estuaries and coasts, and drew from a broader literature if it enhanced our understanding of the ecology or management of these systems.

Our focal literature included 38 studies, mostly occurring in Puget Sound (WA, USA), the Hudson River estuary (NJ & NY, USA), and various locations along the east coast of the United States (Table 1, Fig. 2). Studies examined two major types of armouring: vertical, generally featureless retaining walls made of concrete or wood, which we refer to as ‘seawalls’, and large, angular boulders, which we refer to as ‘riprap’. Inferring from annual citations of these articles, research interest in armouring and overwater structures has emerged over the past 15 years, and interest in mitigating negative effects of armouring has been more recent. Only quite recently have studies examined how to mitigate negative effects of overwater structures on fish.

**Nearshore ecosystems as fish habitats**

Ecologists have long recognized that nearshore areas provide important functions for fish in supporting high productivity, high densities of juvenile fish, and low densities of predators (Beck et al. 2001; Able 2005). Shallow waters and their associated biogenic and geomorphic structures often limit the presence or effectiveness of larger predators, and are inhabited by terrestrial, epibenthic, and planktonic prey (Simenstad, Fresh & Salo 1982; McIvor & Odum 1988; Paterson & Whitfield 2000). Juveniles of many fish species use shallow areas, especially in estuaries, before moving offshore as adults (Deegan 1993; Able 2005). Nursery function of shallow habitats has conventionally been assessed by measuring output of juveniles to adult populations (Beck et al. 2001; Duhlgren et al. 2006); however, habitats can be more directly assessed by examining specific processes and dynamics that facilitate fish development. Ecologists have recently advocated for a sophisticated concept of habitat value, whereby networks of shallow areas benefit juveniles by providing access to appropriate resources (e.g. food, refuge) or environments (e.g. salinity, temperature) as they develop (e.g. Nagelkerken et al. 2015; Sheaves et al. 2015). These discussions underscore the importance of connectivity that allows fish to access habitat networks, and warn that conventional abundance metrics may overlook more direct components of habitat quality. Thus, the value of fish habitats will be better understood by examining processes and dynamics that support fish development (Simenstad & Cordell 2000; Sheaves et al. 2015).

**Documented effects of shoreline armouring on fish**

Studies in many locations have found that armouring influenced localized fish abundances or the composition of fish communities (Hendon, Peterson & Comyns 2000; Peterson et al. 2000; Davis, Takacs & Schnabel 2006; Toft et al. 2007; Pastor et al. 2013; Lowe & Peterson 2014). Some of these studies also found that armoured shorelines supported lower fish community integrity measured by indices such as diversity and richness (Bilkovic & Roggero 2008; Strayer et al. 2012; Balouskus & Targett 2016; Torre & Targett 2016), and lower annual stability of fish abundance and community composition (Seypheyers et al. 2015). Furthermore, armouring along naturally shallow, soft-sediment beaches can create deep, rocky water fronts that are inhabited by larger predators that prefer hard substrates and absent of fish that select for softer substrates (Munsch, Cordell & Toft 2015a). Given extensive documentation that armouring influences community composition, it likely that much of the world’s armoured shorelines support fish assemblages that did not occur historically.

Armouring can also affect the availability and consumption of fish prey along naturally soft shorelines. Epibenthic (e.g. Morley, Toft & Hanson 2012) and terrestrial (e.g. Dugan et al. 2008; Sobocinski, Cordell & Simenstad 2010) invertebrates are negatively impacted along armoured shorelines, presumably because armouring displaces or severs connections to their habitats. Armouring also reduces prey densities by narrowing beaches and limiting the accumulation of wrack that produces invertebrates (e.g. Dethier et al. 2016; Heerhartz et al. 2016). Some fish species along armoured shorelines feed less on terrestrial (Toft et al. 2007) or epibenthic prey (Morley, Toft & Hanson 2012), or switched from feeding on preferred epibenthic prey to plankton (Munsch, Cordell & Toft 2015b). We did not find any studies of armouring effects on coastal and estuarine fish diets outside of Puget Sound, but there is evidence that effects occur elsewhere, for example in lakes in Japan (Doi et al. 2010).

Armouring can also impair other processes such as reproduction and the ability of juveniles to select appropriate habitats as they develop. Intertidal areas are often used for spawning (DeMartini 1999), and armouring can limit this function by eliminating substrate used for egg production.
<table>
<thead>
<tr>
<th>Modification</th>
<th>Ecological response</th>
<th>Major taxa</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riprap only</td>
<td>Abundance</td>
<td>Diplodus sargus</td>
<td>Pastor et al. (2013)</td>
</tr>
<tr>
<td></td>
<td>diversity, size distribution</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abundance, diet</td>
<td>Gobiosoma bosc, Leiostomus xanthurus, Brevoortia patronus, others</td>
<td>Petro et al. (2013)</td>
</tr>
<tr>
<td></td>
<td>Abundance (not detected)</td>
<td>Gobiosoma bosc, Leiostomus xanthurus, Brevoortia patronus, others</td>
<td></td>
</tr>
<tr>
<td></td>
<td>diversity (not detected)</td>
<td>Ophiodon elongatus, Pleuronectiformes, Sebastes melanops, others</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abundance among years, community</td>
<td>Dorosoma cepedianum, Leiostomus xanthurus, Mugil cephalus, others</td>
<td></td>
</tr>
<tr>
<td></td>
<td>composition among years</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abundance, community composition</td>
<td>Anchoa mitchilli, Brevoortia patronus, Mugil curema, others</td>
<td>Lowe &amp; Peterson (2014)</td>
</tr>
<tr>
<td></td>
<td>Abundance, community composition,</td>
<td>Fundulus diaphanus, Lepomis gibbosus, Notropis hudsonius, others</td>
<td>Strayer et al. (2012)</td>
</tr>
<tr>
<td></td>
<td>diversity</td>
<td>Oncorhynchus spp., others</td>
<td>Morley, Toft &amp; Hanson (2012)</td>
</tr>
<tr>
<td></td>
<td>Abundance, diet</td>
<td>Fundulus diaphanus, Leiostomus xanthurus, Menidia menidia, others</td>
<td>Torre &amp; Targett (2016)</td>
</tr>
<tr>
<td></td>
<td>Abundance, community composition</td>
<td>Brevoortia tyrannus, Menidia menidia, Morone americana, others</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abundance</td>
<td>Oncorhynchus spp.</td>
<td>Munsch, Cordell &amp; Toft (2015b)</td>
</tr>
<tr>
<td></td>
<td>Size distribution</td>
<td>Oncorhynchus spp.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(not detected)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abundance, feeding behaviour</td>
<td>Oncorhynchus spp.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(not detected)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Habitats only</td>
<td>Hypomesus pretiosus</td>
<td>Rice (2006)</td>
</tr>
<tr>
<td></td>
<td>Embryo mortality</td>
<td>Oncorhynchus spp., others</td>
<td>Toft et al. (2013)</td>
</tr>
<tr>
<td></td>
<td>(vs. seawalls, riprap)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abundance, community</td>
<td>Atherinopsidae, Clupeidae, Tetraodontidae, others</td>
<td>Peters, Yeager &amp; Layman (2015)</td>
</tr>
<tr>
<td></td>
<td>composition, richness</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(vs. mangroves)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abundance</td>
<td>Fundulus heteroclitus, Leiostomus xanthurus, Lepomis gibbosus, others</td>
<td>Davis, Takacs &amp; Schnabel (2006)</td>
</tr>
<tr>
<td></td>
<td>Marsh &amp; riprap sills*</td>
<td>Lagodon rhomboides, Leiostomus xanthurus, Mugil cephalus, others</td>
<td>Curin, Delano &amp; Valdes-Weaver (2008)</td>
</tr>
<tr>
<td></td>
<td>(vs. seawalls)</td>
<td>Lagodon rhomboides, Leiostomus xanthurus, Mugil cephalus, others</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abundance, diversity</td>
<td>Anchoa mitchilli, Bairdiella chrysoura, Menidia menidia, others</td>
<td>Balouskus &amp; Targett (2016)</td>
</tr>
<tr>
<td></td>
<td>Marsh &amp; riprap sills*</td>
<td>Menidia menidia</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(vs. marshes)</td>
<td>Oncorhynchus spp., others</td>
<td>Balouskus &amp; Targett (2012)</td>
</tr>
<tr>
<td></td>
<td>Abundance, diet, bioenergetic-modelled growth (not detected)</td>
<td>Oncorhynchus spp., others</td>
<td>Cordell et al. (2011)</td>
</tr>
<tr>
<td>Wetland restoration*</td>
<td>Abundance</td>
<td>Anchoa mitchilli, Menidia menidia, Morone saxatilis, others</td>
<td></td>
</tr>
<tr>
<td>(vs. riprap)</td>
<td>Abundance, community</td>
<td>Abudelfad saxatilis, Centropomus spp., Chaeodipterus faber, others</td>
<td>Pereira et al. (2017)</td>
</tr>
<tr>
<td></td>
<td>composition, diversity</td>
<td>Anchoa mitchilli, Menidia menidia, Morone saxatilis, others</td>
<td>Able, Grothues &amp; Kemp (2013)</td>
</tr>
<tr>
<td></td>
<td>Abundance</td>
<td>Oncorhynchus spp., others</td>
<td>Toft et al. (2007)</td>
</tr>
<tr>
<td></td>
<td>Abundance, feeding behaviour</td>
<td>Oncorhynchus spp., others</td>
<td>Munsch et al. (2014)</td>
</tr>
<tr>
<td></td>
<td>Abundance, swimming behaviour</td>
<td>Oncorhynchus spp.</td>
<td>Southard et al. (2006)</td>
</tr>
</tbody>
</table>

Note: Asterisks indicate shoreline features evaluated as ecologically preferable alternatives to conventional infrastructure.

Table 1. Focal literature describing effects of shoreline modifications on fish ecology in estuarine and coastal systems.
deposition (Balouskus & Targett 2012), or by replacing spawning beaches with unvegetated, impervious substrates that increase embryo mortality through excessive exposure to sunlight, heat and dryness (Rice 2006). Furthermore, naturally sloped intertidal zones can support scaled ontogenetic habitat shifts, whereby fish use incrementally

**Table 1.** (Continued)

<table>
<thead>
<tr>
<th>Modification</th>
<th>Ecological response</th>
<th>Major taxa</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeding</td>
<td>Feeding</td>
<td><em>Pseudopleuronectes americanus</em></td>
<td>Duffy-Anderson &amp; Able (2001)</td>
</tr>
<tr>
<td>Feeding, growth</td>
<td>Microgadus tomcod</td>
<td><em>Pseudopleuronectes americanus, Tautoga onitis</em></td>
<td>Metzger, Duffy-Anderson &amp; Able (2001)</td>
</tr>
<tr>
<td>Piers &amp; pile fields</td>
<td>Abundance</td>
<td><em>Anchoa mitchilli, Menidia menidia,</em></td>
<td>Grothues, Rackovan &amp; Able (2016)</td>
</tr>
<tr>
<td></td>
<td>Feeding, growth</td>
<td><em>Bairdiella chrysoura, Gobiosoma bosc,</em></td>
<td>Able, Manderson &amp; Studholme (1998)</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Fundulus heteroclitus,</em> others</td>
<td>Able, Manderson &amp; Studholme (1999)</td>
</tr>
<tr>
<td>Light-penetrating surfaces under piers*</td>
<td>Abundance</td>
<td><em>Oncorhynchus spp.</em></td>
<td>Ono &amp; Simenstad (2014)</td>
</tr>
</tbody>
</table>

**Fig. 2.** Top: time series of interest in research examining effects of shoreline modifications on fish, and mitigating negative effects. See Appendix S1, Supporting Information for a detailed description of how we produced this figure. Bottom: locations of studies cited above, panelled by type of shoreline modification. Numbers indicate multiple studies in the same system.
deeper habitats as they grow (Munsch, Cordell & Toft 2016). These shifts may occur because larger predators are uncommon in extreme shallows, larger fish are less vulnerable to predation and fish balance the safety of shallows with other benefits of maximizing habitat use (e.g. foraging in less spatially constrained environments). Fish can be larger along armoured shorelines compared to unarmoured shorelines (Davis, Takacs & Schnabel 2006; Munsch, Cordell & Toft 2016), presumably because armoured shorelines lack protective shallows. Overall, it appears that armouring can impair habitat functions and processes including predator refuge, prey production, reproduction and ontogenetic habitat shifts.

Armouring effects are not universal among ecosystems or species. For example, some studies did not observe armouring effects on fish abundances or diversity (Seitz et al. 2006; Lawless & Seitz 2014) or found that armouring did not influence movement patterns or feeding behaviour (Heerhartz & Toft 2015). Some studies detected differential effects, such as on fish abundances in marshes but not subtidal areas (Gittman et al. 2016), on community integrity along seawall but not riprap shorelines (Bilkovic & Roggero 2008) or on diets of some but not all species (Munsch, Cordell & Toft 2015b). Also, some studies found that certain fish species were more abundant along armoured shorelines (e.g. Pastor et al. 2013; Munsch, Cordell & Toft 2015a). It appears that effects are most evident in species that extensively use habitat components affected by armouring (e.g. Oncorhynchus keta that target shallow epibenthic prey; Munsch, Cordell & Toft 2015b) or in systems where armouring is extensive (e.g. riprap that extends into subtidal zones; Toft et al. 2007).

Documented effects of overwater structures on fish

Many fish are visually oriented and sudden decreases in light can reduce their performance of visual tasks (Ali 1959), which may cause them to avoid shaded areas under overwater structures. Total abundances of fish can be substantially reduced in areas shaded by piers (Southard et al. 2006; Able, Grothues & Kemp 2013). Juvenile salmon Oncorhynchus spp. in Puget Sound use shorelines as migratory corridors and aggregated next to piers as while avoiding pier shade, generating concern that piers interrupt their seaward migrations by constraining movements along shore (Toft et al. 2007; Munsch et al. 2014). In the Hudson River estuary, predators aggregated in shaded areas at the edge of piers, potentially to ambush smaller fish (Able, Grothues & Kemp 2013). Effects appear to be primarily driven by shade rather than piling structures, as evidenced by observations of fish movements relative to pier shade (Ono & Simenstad 2014) and comparisons among nearshore waters that are open, within uncovered piling fields and under overwater structures (Able, Manderson & Studholme 1998; Duffy-Anderson, Manderson & Able 2003). However, one study in the Hudson River estuary observed similarly low abundances of fish in uncovered piling fields and under piers relative to open waters, potentially because pilings may disrupt the formation of schools or hide ambush predators (Grothues, Rackovan & Able 2016). Conversely, fish were more abundant and of a different trophic structure under a comparatively narrow pier and bridge along the estuary of Rio Formoso (PE, Brazil), probably because the piling structures provided unique prey, and the shade cast by these structures was less intense than in other studies (Pereira et al. 2017).

Studies have shown empirically that overwater structures can reduce feeding. Caging experiments indicate that some visually feeding fish such as juvenile winter flounder Pseudopleuronectes americanus are unable to feed in shaded areas under piers (Duffy-Anderson & Able 2001) and experience reduced (Metzger, Duffy-Anderson & Able 2001) or negative (Duffy-Anderson & Able 1999) growth despite adequate prey availability (although piers can reduce prey abundances; Cordell et al. 2017). Similarly, when free-swimming fish occur under piers, they can be less likely to attack prey (Munsch et al. 2014). Observations compared to uncovered piling fields suggest effects are driven by shade rather than pilings (Able, Manderson & Studholme 1998). Overall, it appears that overwater structures that create intensely dark environments can reduce (i) localized habitat value by impairing visual tasks (e.g. feeding, predator vigilance) and reducing prey availability and (ii) habitat connectivity by constraining movements along shorelines.

Documented and prospective opportunities to improve modified fish habitats

Nearshore fish habitats can be rehabilitated to varying degrees within constraints of waterfront human use (see Dyson & Yocom 2015 for designs in urban systems) (Figs 3 and 4), and there is growing, experimental interest in designing shoreline features that promote ecological functions. Detrimental effects of armouring and overwater structures generally fall into categories of connectivity and accessibility, prey availability, predation risk and reproduction (Table 2). These habitat attributes may be improved by shoreline features that add complexity to the substrate, replicate or restore low-gradient beaches, add backshore vegetation and mitigate overwater shading.

Along shorelines where human use makes true restoration impractical, intertidal grades can be replicated to create connected shallows. One approach is to construct waterfronts using nature-based materials to avoid or minimize the use of armouring (i.e. ‘living shorelines’). For example, low-profile riprap breakwaters along shorelines can create space for landward, inundated marshes (i.e. ‘riprap sills’). These designs provide protection from erosion, and can support densities and diversities of fish that are equivalent or even greater than at naturally occurring
some fish can also deposit eggs along riprap sills in greater densities than along seawall and riprap shorelines and comparable to natural marsh shorelines (Balouskus & Targett 2012). However, responses of fish to living shorelines can also be ambiguous, such as along waterfronts constructed with riprap in front of mangroves that supported less abundant, but more diverse fish assemblages compared to natural mangroves (Peters, Yeager & Layman 2015). In another example, restored off-channel marshes supported greater Chinook salmon *Oncorhynchus tshawytscha* abundances and different prey resources than unrestored areas, but effects on bioenergetics-modelled growth were not detected (Cordell *et al.* 2011). These studies suggest that ecological functions of nature-based shorelines can vary among designs and settings. Shorelines stabilized by...
oyster reefs are another potential alternative to armouring that can increase localized fish abundances (e.g. Scyphers et al. 2011), but fish responses have yet to be evaluated relative to armoured shorelines. These results are generally encouraging, and there are other potential benefits of nature-based approaches that have yet to be fully evaluated, such as predator refuge and feeding opportunity.

Studies have recently explored alternative mitigation strategies in highly urbanized settings. A riprap and seawall shoreline was replaced by two shoreline types that created shallow, low-gradient waters that were robust to erosion: a sediment-nourished pocket beach with backshore vegetation and a habitat bench composed of compacted substrate in front of conventional concrete infrastructure (Toft et al. 2013). Compared to armoured shorelines, these features provided greater densities of some epibenthic and terrestrial prey, and, in some years, greater densities of larval fish, juvenile fish and incidence of feeding behaviour. Their shallow sloping waters provided a gradient of depths used by different ontogenetic stages of fish, whereas these ontogenetic habitat shifts were not observed along shorelines where armouring eliminated shallows (Munsch, Cordell & Toft 2016). Other designs that have yet to be evaluated in the context of fish habitat include ‘habitat skirts’ that create shallow-water shelves along pier margins (Slogan 2015), rock pools in seawalls (Chapman & Blockley 2009), adding texture and relief to seawalls (Cordell et al. 2017) and waterfront vegetation that overhangs aquatic habitats, which may increase invertebrate prey production or, in some cases, provide protective shallows. Overall, restoring or enhancing the elevational gradients and complexity of shorelines may create habitat corridors along developed waterfronts where fish have sufficient access to prey, reproductive areas and shallow refuges from predators.

Shade cast by overwater structures can be mitigated along shorelines to restore normal habitat use by fish. Active lighting can illuminate areas under piers, although the associated electronics must be durable and their light distributed evenly because fish may avoid excessively bright areas (Ono & Simenstad 2014). In addition, purchase and maintenance costs for artificial light may be prohibitive, and a more pragmatic solution is to integrate passive light-penetrating surfaces (e.g. glass panels, metal grating, skylights) into overwater structures. A pilot study suggested light-penetrating surfaces could improve juvenile Chinook salmon access to areas under piers (Cordell et al. 2017). As a result, the City of Seattle (WA, USA) has initiated large-scale integration of glass blocks into overwater structures along its downtown waterfront to create a migration corridor for anadromous salmonids (Cordell et al. 2017). Its effectiveness in allowing fish to swim normally under piers has yet to be evaluated. Other options to mitigate shading that have yet to be tested on fish include: increasing the height of overwater structures relative to water levels; decreasing overwater structure widths, particularly near shore; orienting overwater structures perpendicular to the sun’s arc; using reflective materials or paint; and avoiding dense pilings (Nightingale & Simenstad 2001).

**Moving forward: filling knowledge gaps and adjusting practices**

There is still much to be learned by evaluating shoreline habitats. We need to understand why fish select for certain shoreline attributes by expanding habitat assessments to focus more on metrics that directly indicate fish habitat value (Sheaves et al. 2015). Studies conventionally evaluate habitat using abundance metrics, which can imprecisely measure habitat quality because (i) abundance is

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**Table 2. Categories of habitat attributes and examples of assessments to examine them**

<table>
<thead>
<tr>
<th>Habitat attribute</th>
<th>Assessment examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connectivity and accessibility</td>
<td>• Do physical or behavioural (e.g. shade avoidance) barriers prevent fish from accessing appropriate resources or environments?</td>
</tr>
<tr>
<td></td>
<td>• Are there continuous shallow waters along shore?</td>
</tr>
<tr>
<td></td>
<td>• Do areas of low predation risk overlap with favourable foraging areas?</td>
</tr>
<tr>
<td>Prey availability</td>
<td>• Are appropriate prey available, i.e. how do prey assemblages and fish diets compare to more natural conditions?</td>
</tr>
<tr>
<td></td>
<td>• If prey availability differs, do fish consume alternatives, and at what costs (e.g. energy content or evasion capabilities of prey)?</td>
</tr>
<tr>
<td></td>
<td>• Is the prey assemblage appropriate for all juvenile phases, i.e. does the prey field allow for ontogenetic diet shifts?</td>
</tr>
<tr>
<td>Predation risk</td>
<td>• Is refuge from predators available? In particular, is there a shallow depth gradient available to provide predator refuge or mediate ontogenetic habitat shifts?</td>
</tr>
<tr>
<td></td>
<td>• Are substrates or biogenic structures appropriate for the fish assemblage (e.g. sand that enables burrowing, eelgrass and kelp that provide cover)?</td>
</tr>
<tr>
<td></td>
<td>• Do habitat features attract predators or create environments that are advantageous for predators?</td>
</tr>
<tr>
<td>Reproduction</td>
<td>• Are appropriate substrates available for spawning (e.g. beaches, vegetation).</td>
</tr>
<tr>
<td></td>
<td>• Is the physical energy regime appropriate for larval fish?</td>
</tr>
</tbody>
</table>
only loosely correlated with true habitat value conferred by dynamic functions and processes (Sheaves et al. 2015) and (ii) fish are mobile and may be locally abundant only temporarily or present incidentally along migration routes (Simenstad & Cordell 2000). In addition, ecologists must consider that causing fish to aggregate around some shoreline features may increase competition or lead to resource depletion in surrounding areas (sensu Edelst & Spanier 2009). Ecologists can more directly assess habitat quality and fitness, including within restoration contexts, by examining capacity features that promote fish production (e.g. prey availability and physical conditions), habitat accessibility (e.g. tidal flooding and environmental conditions) and realized function (e.g. growth and feeding behaviour; Simenstad & Cordell 2000). It is important that we verify habitat improvement efforts address these direct determinates of habitat quality and refine improvement efforts accordingly (sensu Fischman & Ruhl 2016) to avoid ‘carrying out ecological modifications which are neither guaranteed to be necessary or successful but rather which make society (including ecologists) feel as though something is being done’ (Elliott et al. 2016). Given that we know shoreline modifications affect fish assemblages in many locations and that assessing nearshore biota is becoming feasible on large scales (e.g. environmental DNA sampling; Kelly et al. 2016), it is increasingly important that we connect patterns in community composition to specific habitat attributes and ecological functions so that conservation efforts can address determinates of habitat quality directly. Our understanding would benefit from manipulative studies (e.g. enclosing fish near shore) to verify localized costs and benefits (e.g. bioenergetics, predation) of occupying modified and enhanced shorelines, respectively. For example, we poorly understand the bioenergetic consequences of fish feeding on alternative prey (e.g. lower energy content, more evasive) along armoured shorelines. Likewise, fish tracking studies examining habitat selection as it relates to shoreline modifications and improvements would allow us to better understand their costs and benefits to fish (e.g. opportunity costs of searching for appropriate habitats).

Our ability to manage nearshore fish habitats is also limited by gaps in our knowledge about their natural histories. Natural history encompasses the fundamental traits of organisms – what they are, how they behave, and how they interact with their environments and other biota (Tewksbury et al. 2014). In fish, this understanding is often incomplete (Able 2016), in part because studies typically use capture-based methods that preclude or degrade information on behaviour and habitat use. Natural history information can guide local habitat improvements and place these efforts in the broader context of conserving fish populations; for example by empirically understanding: (i) species, life-history stages and life-history types that use shallows directly next to shore; (ii) food webs, accounting for ontogenetic diet shifts and prey selection; (iii) habitat features that produce prey, provide protection from predators or facilitate reproduction; and (iv) the contribution of juveniles rearing in nearshore waters to the ultimate production of the species (Beck et al. 2001). Understanding fish responses to shoreline modifications or habitat enhancements in a natural history context can also aid resource managers in making intuitive decisions to align fish conservation efforts with other goals (e.g. oyster recruitment, kelp habitat conservation). Understanding fish natural histories will also allow us to better evaluate the relative benefits of shoreline geomorphology (e.g. sloping waters that protect smaller fish) and engineering materials (e.g. substrates that facilitate prey production), allowing us to maximize desired restoration benefits occurring within budgetary and human-use constraints. Natural history information is often collected passively (e.g. by-product of research and local ecological knowledge) and this information could be disseminated at relatively small cost (e.g. FishBase; Tewksbury et al. 2014).

Finally, it is important to identify which species, ecosystems or processes to prioritize for protection so that fish responses to shorelines can be understood in the broader context of conservation. For instance: (i) diversity metrics without context can mislead us about habitat condition or ecological function in systems that naturally serve as nurseries for a small number of highly abundant species; (ii) urban systems may be practically impossible to restore, but it is unclear whether management should support present, potentially novel fish assemblages or prioritize recreating components of the pre-existing ecosystem (Hobbs et al. 2014); and (iii) some fish of management interest (e.g. predators and protected species) may benefit from modified shorelines at the expense of fish that benefit from unmodified shorelines.

Managing socio-ecological systems

Efforts to improve nearshore fish habitats should embrace their socio-ecological roles and leverage appreciation for local nearshore ecosystems. Restored or enhanced public shorelines can promote recreational spaces, provide educational opportunities (e.g. organized events and kiosks; Fig. 5) and connect people with the natural world in urban landscapes (sensu Hobbs et al. 2014). Exposing people to local ecology may create connections between people and their local shoreline ecosystems, and encourage taxpayers or private property owners (see Seyphers, Picou & Powers 2015) to invest in functional waterfront ecosystems. Fish responses to habitat rehabilitation along urban recreational shorelines have only begun to be evaluated (Toft et al. 2013; preliminary observations by Reid et al. 2015), and these juxtapositions of human and fish use should be further explored because they can demonstrate how goals of resource management and other human uses can be aligned. Furthermore, as climate change and sea level rise increase flooding risk, nature-based coastal defences offer cost-effective and
ecologically beneficial alternatives to conventional shoreline infrastructure (Temmerman et al. 2013). Shoreline restoration projects can also stimulate local economies by generating jobs and improving property values (Edwards, Sutton-Grier & Coyle 2013; NOAA 2016). Thus, there is great potential to align ecological, economic and human safety goals through shoreline rehabilitation projects (Elliott et al. 2016).

Conclusions

Shoreline infrastructure modifies much of the world’s shorelines and drives change in the ecology of fish. In many cases, this has resulted in impairment to habitats of shoreline-oriented fish. Habitat enhancement (Toft et al. 2013), ecological engineering (Bergen, Bolton & Fridley 2001) and educational efforts often require only a fraction of project budgets when building or replacing shoreline infrastructure, yet they can provide habitat functions for fish while maintaining or improving the value of shorelines to society. Many urban waterfronts are so removed from natural ecosystems that return to historical conditions is impractical (Hobbs et al. 2014), and urban settings provide experimental systems to develop modern habitat features that function within the constraints of waterfront use by people. It is clear from our review that we can move beyond conventional waterfront designs dominated by large, impervious surfaces that impair fish habitats, provide little protection from flooding and create precarious situations of sea levels rising against built shorelines (i.e. coastal squeeze; Doody 2004; Temmerman et al. 2013). An updated management framework that improves fish habitats along developed shorelines can benefit from: (i) research focusing on metrics that describe habitat quality and fitness; (ii) continued development and evaluation of shoreline features that repair compromised habitat functions within human-use constraints; (iii) collating regional knowledge of fish natural histories to streamline habitat improvement efforts; and (iv) targeting overlapping socio-ecological goals of improving fish habitats, receiving ecosystem services and increasing public appreciation of waterfront ecosystems.

By the 8th century, Ancient Alexandria entered a dark age. Much of its original waterfront is now underwater because Roman engineers were unable to construct a waterfront resilient to earthquakes, tsunamis and subsidence (Lawler 2005). Modern shorelines are built similarly, leaving coastal civilizations vulnerable to environmental stressors and burdened by maintenance costs of conventional infrastructure. Given current challenges of climate change, sea level rise and increasing coastal populations, we should invest in shoreline ecosystems that benefit fish and people over the long term.

Authors’ contributions

S.H.M. conceived and led the writing of the manuscript. All authors contributed intellectual content, critically revised the manuscript and approved the final draft.

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Data accessibility

Data have not been archived because this article does not contain data.

References


Fig. 5. Kiosk along the downtown Seattle (WA, USA) waterfront describing the local nearshore ecosystem and why a beach provides better habitat than the previous armoured shoreline.


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**Supporting Information**

Details of electronic Supporting Information are provided below.

**Appendix S1.** Creating a time series describing research interest in our focal literature.