Chapter 25

Can Bivalve Habitat Restoration Improve Degraded Estuaries?

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1. INTRODUCTION: BIVALVES—THE FORGOTTEN HABITAT BUILDERS

Bivalve habitats have, until recent times, been generally overlooked as an important estuary habitat type. Historically, complex, three-dimensional habitats made up of dense aggregations of bivalves, their shells, associated species, and accumulated sediments were a dominant habitat type in temperate and subtropical estuaries around the world (Stenzel, 1971). These habitats were generally engineered by oyster (generally referred to as reefs) or mussel (generally referred to as beds) species. Until recent times these habitats were primarily managed as an important fisheries resource. Their historical extent and importance are difficult to estimate because bivalve habitats were often decimated before fisheries records were collected systematically, and there may be no remaining visible functioning bivalve habitats. Through the process of historical amnesia, or shifting baselines, successive generations of local people, and managers have grown accustomed to the new norm and have forgotten about the former abundant bivalve habitats.

Bivalve habitats are threatened globally. In a comprehensive review Beck et al. (2009, 2011) estimated that 85% of oyster reefs were lost globally and oyster reefs were functionally extinct (> 99% loss) in 37% of estuaries. There are likely to be vast but largely unquantified losses of other habitat-forming bivalves. For example, formerly widespread green-lipped mussel (*Perna canaliculus*) beds in New Zealand, appear to occur at less than 1% of historical levels (McLeod, 2009; Paul, 2012). These losses are greater than those reported for other important estuary habitats including coral reefs, mangroves, and seagrasses (Grabowski et al., 2012). The loss of this fishery resource has had devastating effects on the coastal communities that relied on the harvest of bivalve habitats for employment and food.

Recently, benefits of bivalve habitats other than as a fishery resource have been recognized and bivalve restoration has expanded to focus on restoring reefs and beds to boost local fish and crustacean fisheries, improve water quality, and protect shorelines (zu Ermgassen et al., 2016a). The economic value of the full suite of ecosystem services derived from natural oyster reefs in North America was recently estimated to be as high as US\$106,000 ha^{-1} $year^{-1}$ (all values converted to 2017 \$USD values by inflating in line with the annual average consumer price index; Grabowski et al., 2012), which is higher than estimates for other habitats such as mangroves (\$82,000 ha^{-1} $year^{-1}$; Balmford et al., 2002), seagrass (\$31,000 ha^{-1} $year^{-1}$; Grabowski et al., 2012), and permanent wetlands (\$21,000 ha^{-1} $year^{-1}$; Sutton and Costanza, 2002).

Bivalve habitat restoration for ecosystem services has been scaling up in the United States and is increasingly being undertaken worldwide as a way to improve estuary condition and bring back an imperiled ecosystem. However, estuaries have changed vastly through centuries of fishing, coastal development, habitat disturbance, sedimentation, and eutrophication. Bivalve habitats also face new challenges such as a changing climate, increasing ocean acidification and introduced predators, competitors, and diseases. This chapter discusses what scale of bivalve habitat restoration is possible worldwide, what positive influences restoration can make to degraded estuaries, and considers these within the context of a rapidly changing coastal environment.

2. WHAT ARE BIVALVE HABITATS?

There are numerous historical accounts of vast expanses of habitat-building bivalves throughout the historical literature. They describe highly complex structures of successive generations of bivalves forming expansive "barriers" or "banks" (Fig. 1; zu Ermgassen et al., 2016a), in some cases on the scale of "a mile in length" (Brooks et al., 1884). Defining bivalve reefs or beds is, however, something that has challenged observers since these early descriptions.

Bivalve reefs and beds are complex biogenic structures formed by successive generations of bivalves settling out and growing on top of one another. Within them, the habitat-building species are found at high density, while the dead shell material may dominate the structure. The term "bivalve reefs" generally applies to habitats with significant vertical relief (> 0.5 m; Beck et al., 2009), whereas "bivalve beds" have a lower relief (sensu Coen and Grizzle, 2007). In both cases, the structures formed tend to accrete through time, as shell matter is deposited at rates greater than those lost to sedimentary dynamics (Mann et al., 2009). Most bivalve reefs today are less than 1 m high but there are massive, dead, biogenic reefs built by the European oyster, *Ostrea edulis* in the Bulgarian Black Sea up to 7 m above the seabed (Todorova et al., 2009) and subtidal shell reefs in Port Stephens, Australia up to 8 m above the seabed (Ogburn et al., 2007). Nevertheless, these habitats are far from permanent at individual locations within and along the dynamic estuaries

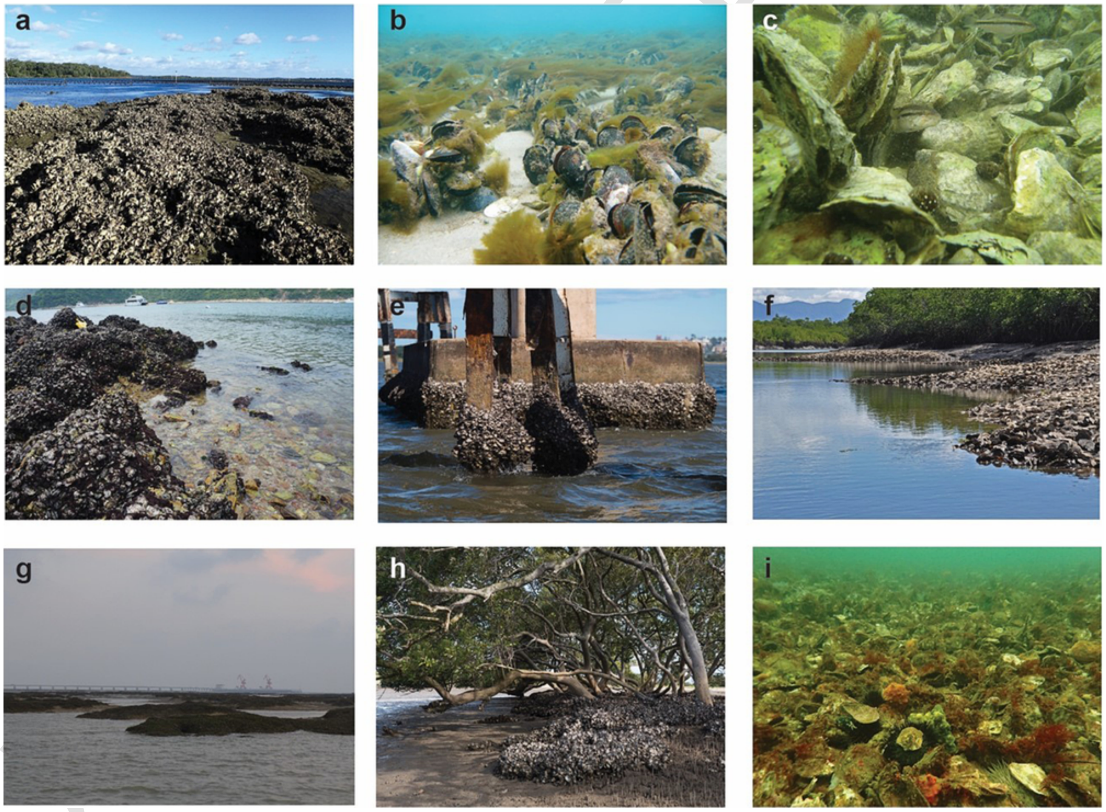

FIG. 1 Bivalve habitats. (A) Intertidal Sydney rock oyster, *Saccostrea glomerata*, growing on a mud bank in Port Stephens, New South Wales, Australia. (B) Subtidal green-lipped mussel, *Perna canaliculus*, bed growing on sand in an estuary channel in the Hauraki Gulf, New Zealand. (C) Subtidal eastern oyster, *Crassostrea virginica*, with a juvenile black sea bass, *Centropristis striata*, (located at the center of the image) Block Island, Rhode Island, United States. (D) Hooded oyster, *Saccostrea cucullata*, growing on a rocky shoreline, Hong Kong, China. (E) *S. glomerata* growing on wharf pilings in Port Stephens, Australia. (F) Leaf oysters, *Isognomon ephippium* growing on a mud bank in Hinchinbrook Channel, Queensland, Australia. (G) Liyashan Reef, made up of *Crassostrea sikamea* growing on mud flats, Jiangsu Province, China. (H) *S. glomerata*, growing on mangrove roots and pneumatophore in Port Stephens, New South Wales, Australia. (I) Subtidal flat oyster, *O. angasi*, reef in Tasmania, Australia. *(Photos from (A) I. McLeod. (B) I. McLeod. (C) S. Brown. (D) D. McAfee. (E) McLeod. (F) McLeod. (G) J. Cheng. (H) S. McOrrie.)*

and coasts where they are predominantly found. While habitat-forming bivalves are considered to be the basis of reef structures analogous to coral reefs but in temperate estuaries (Stenzel, 1971), the exact location and height of reefs within these systems has always changed over time, as vast historical fossilized oyster reefs in many Gulf of Mexico (United States) estuaries illustrate (May, 1971). Mussel beds are similarly known to be both transient and long lived in the estuaries in which they are found (Dankers et al., 2001). That said, at a large scale, these reefs and bed systems have been dominant in temperate waters for millennia (Stenzel, 1971).

It has been a challenge for ecologists and coastal managers to consistently define bivalve reefs for the purpose of mapping their extent and determining the extent and success of restoration efforts. Generally, definitions focus on the dominance of shell material in the structure of these bivalve habitats, and/or a minimum density of live bivalves (Baggett et al., 2014; OSPAR Commission, 2009), which serve as an indicator that the habitat is accreting, or at least persisting over time. Defining and mapping bivalve habitats are further challenged by the natural tendency for them to be patchy; often with reef "islands" separated by soft mud, or large reefs encompassing significant patches of soft bottom material (Fig. 1). These systems are highly fractal in their nature, with patchiness occurring at numerous spatial scales. It is therefore important to provide clear information about the scale and resolution at which mapping was undertaken. To this end, the United States National Oceanic and Atmospheric Administration (NOAA), The Nature Conservancy (TNC), and other partners have drafted guidelines for mapping and reporting oyster restoration efforts in the United States, which account for the challenges presented by varying scales and which provide a useful reference for other geographies at they move forward with their own restoration efforts (Baggett et al., 2014, 2015).

3. ECOSYSTEM SERVICES

The benefits that humans derive from nature are broadly referred to as ecosystem services. While all bivalve habitats are likely to provide some degree of ecosystem goods and services, the exact nature and quantification of these services is best studied in the eastern oyster, *Crassostrea virginica*. *C. virginica* forms extensive reefs in estuarine areas of the Atlantic and Gulf of Mexico coasts of the United States and have been documented to provide a suite of ecosystem services including, but not limited to improved water clarity and water quality, enhancing fish and invertebrate production, and reducing coastal erosion (Coen et al., 2007). The bivalve shell material forms complex three-dimensional habitats which can trap sediments and buffer wave energy and be used by sessile and mobile-associated species for attachment or protection. The bivalves produce feces and pseudofeces, which provide a rich material for detritivores and bacterial communities that remove nitrogen from the water column. These ecosystem goods and services are critical in supporting the livelihoods and social fabric of coastal communities.

Bivalves are filter feeders that improve water clarity by drawing down and filtering out particles from the water column. The edible particles are consumed and later deposited as feces, whereas the inedible particles are bound up in mucus and ejected as pseudofeces. In either case, the particles are drawn from the water column and deposited to the benthos, a process which both decreases turbidity in the water and which enriches the sediments with bioavailable carbon and nitrogen. The improved water clarity can both increase the amenity value of an area (Choe et al., 1996), and encourage the growth of seagrasses (Wall et al., 2008), which are themselves highly valuable habitats. Meanwhile, enriching the sediments with nutrient-rich compounds acts to stimulate the activity of denitrifying bacteria, which convert biologically active nitrogen to inert dinitrogen gas (Newell et al., 2002). Furthermore, the shell surface area and the additional structural complexity around the reef provides an ideal environment for this microbial action to take place, as it creates many sites where aerobic and anaerobic activity are in close proximity (Humphries et al., 2016). This process of enhanced denitrification alone has been valued at an average of \$4050 ha^{-1} year^{-1} (Grabowski et al., 2012).

Oyster reefs are consistently found to support higher biodiversity and abundance of species than nearby unstructured habitats (e.g., Moebius, 1883; Shervette and Gelwick, 2008). The three-dimensional complex habitat provided by oyster reefs provides an important refuge from predation for many invertebrates and juvenile fish species (Tolley and Volety, 2005; Humphries et al., 2011), while the oysters themselves are prey for a number of larger fish species such as black drum, *Pogonias cromis* (Brown et al., 2008). A review of which species were consistently enhanced as juveniles by oyster reefs in the Atlantic coasts and Gulf of Mexico of the United States identified 12 and 19 species, respectively (zu Ermgassen et al., 2016b). This enhancement of large crustaceans and juvenile fishes is believed to contribute 2.8 and 5.3 t^{-1} ha^{-1} of oyster reef year^{-1}, respectively, to the system as a whole (zu Ermgassen et al., 2016b, updated tables available in zu Ermgassen et al., 2016a at http://oceanwealth.org/tools/oyster-calculator/). While quantitative evidence from other species is scant, green-lipped mussel, *Perna canaliculus*, beds in New Zealand have been shown to provide 3.5 times the productivity of invertebrates and host 13 times the density of small fishes than nearby soft sediments

(McLeod et al., 2013). Furthermore, there are numerous qualitative accounts of bivalve species such as *Modiolus modiolus*, *Pinna* spp., *Atrinia* spp., *O. edulis*, and *Crassostrea rivularis* supporting enhanced biodiversity (Moebius, 1883; Barnes et al., 1973; Quan et al., 2012a; Ragnarsson and Burgos, 2012).

Oyster reefs can be robust structures with significant vertical relief that can have similar coastal defense properties as low-crested human-built structures such as break-waters, groynes, seawalls, dykes, or other rock-armored structures, through their effects on water circulation behavior and sediment transport. Therefore, they can be designed as effective coastal protection for erosion control and flood reduction (Reguero et al., 2018). There are reports oyster reefs as high as 3 m in the Yellow Sea (China), whereas in the United States, many extant oyster reefs are between 0.5 and 1 m in height. Where they are found in the shallow subtidal or intertidal zones, they have been documented to reduce coastal erosion of the shoreline, although typically only where wave energies are low (Piazza et al., 2005; Scyphers et al., 2011; La Peyre et al., 2015). This happens as a result of the oyster reefs absorbing waves in ways similar to a constructed breakwater and dissipating the energy. A generalized tool to help visualize the wave energy reduction from this “breakwater” effect of oyster reefs is available at https://vimeo.com/21810285. The effectiveness of this ecosystem service is dependent on the location and prevailing hydrodynamic conditions in each case (Piazza et al., 2005; Scyphers et al., 2011; La Peyre et al., 2015).

While the quantitative evidence for ecosystem service provision from other bivalve species is limited, there is good reason to suppose that all bivalve habitats provide at least some of these services. All habitat-building bivalve species are ecosystem engineers; creating structure from their successive generations of shell material, and producing biodeposits as a result of their feeding activity. The magnitude and degree of habitat building is dependent upon the population dynamics of bivalves, which are mediated by factors such as salinity, temperature, turbidity, substrate type, disease, and predation (Powell et al., 2003). It is the sustainable growth of bivalve habitats that facilitates ecosystem engineering properties and the basis of the ecosystem services they provide (Powell et al., 2006; Walles et al., 2015).

4. HISTORIC EXTENT AND FISHERIES

Like other marine resources, bivalve reefs and beds were once considered inexhaustible. This was a logical conclusion judging from their former vast abundance, and for thousands of years this was largely true. Habitat-forming bivalves have had high cultural value and served as the social backbone for indigenous populations around the world for thousands of years (Rick and Erlandson, 2009). They provided an easily accessible, protein-rich source of food and shellswere used as cutting and scraping tools, building materials, fish hooks, jewelry, and currency. The use of these resources is evidenced through the generation of historical bivalve middens (piles of discarded shells), which are found in most temperate coastal areas (Alleway and Connell, 2015). Some of these middens were massive. For example, one shell midden in New South Wales (Australia) was estimated to have a volume of 33,000 m^3, which contained 23,100 t of oyster shells (Bailey, 1975). These middens provide clues to the magnitude of indigenous harvests. Bailey (1975) estimated that the pre-European annual consumption was 17 t of oysters $year^{-1}$. This estimate is similar to the mean annual output of the local oyster fishery during their peak in the mid-20th century (Bailey, 1975). A recent study analyzing shells from middens around the Chesapeake Bay showed that harvests were sustained for 3000 years before European settlement (Rick et al., 2016). Other research from Florida (Sampson, 2015) and New York’s Hudson River Estuary (Claassen and Whyte, 1995) also suggest limited pre-European impacts. However, research into indigenous harvest in the southeast United States (Dame, 2009) and Denmark (Milner, 2013) provided evidence of local depletion. Overall, it is likely that preindustrial populations mostly affected only local and shallow or intertidal populations, leaving subtidal populations as a source to replenish stocks.

It is difficult to comprehend the scale and importance of bivalve reefs and beds historically. Even in contemporary times comprehensive bivalve stock surveys are often only undertaken long after large-scale extraction has begun. Some examples illustrate the general trends. Oyster reefs were so extensive in estuaries on the Atlantic and Gulf Coasts of the United States that they were considered to be a navigation hazard (Coen and Grizzle, 2007). Whereas on the Pacific coast in Willapa Bay (Washington, United States) oysters may have dominated over a quarter of the bay bottom (Blake and Zu Ermgassen, 2015) with descriptions of “natural oyster-beds stretched over a distance of thirty miles in length and from four to seven in width” (Bancroft, 1890). The most extensive oyster grounds surveyed in North America included 25,500 ha in Tangier and Pocomoke Sounds (Chesapeake Bay, Virginia, United States) in 1878 and 16,500 ha in Matagorda Bay, Texas (United States) in 1907–75 (zu Ermgassen et al., 2012). Over a century ago, one-fifth of the Dutch part of the North Sea was covered with *O. edulis* beds (Gercken and Schmidt, 2014). Early explorers to Australia commonly described extensive oyster reefs. For example, the explorer Vancouver ran his vessel aground on a bank of oysters while attempting to leave a Western Australia estuary in 1791. Making light of the situation, Vancouver and his men feasted on the oysters and named the estuary Oyster Harbor (Gillies et al., 2015).

Commonly, intertidal bivalve populations in sheltered bays and coastal waters were the first to be harvested and overharvested because they were readily accessible. Increasing technology innovations such as improved boats, long-handled tongs, and small dredges allowed for more intensive harvesting of reefs and beds and access to deeper and more remote areas. Sailing cutters dragging small iron dredges were probably used as early as the 13th century (Seaman and Ruth, 1997). This early fishery was economically important, highlighted by often violent conflict between Danish and German fishers (Gercken and Schmidt, 2014). Large-scale declines in bivalve habitats were recorded as early as 1695, with 10 oyster banks in the North Sea considered ruined by overfishing and cold winters (Gercken and Schmidt, 2014).

The scale of peak bivalve harvests worldwide is impressive. The mid to late 1800s marked peak harvest years in Europe, North America, and Australia and the rapid devastation of many reefs and beds. In 1864, 700 million *O. edulis* were consumed in London, employing up to 120,000 men in Britain to dredge oysters (MacKenzie et al., 1997). In France more than 100 million oysters were harvested annually during peak years in the 19th century (Yonge, 1960). In the Chesapeake Bay, peak production during the 1880s reached 20 million bushels of oysters annually (2 billion oysters or 900,000 t). These peak harvests took place during the development of machine-driven vessels that could deploy larger, heavier harvesting gear and allowed exploitation of deeper reefs, and access to more remote locations. Increasingly efficient transportation such as railways and greater use of preservation techniques such as using ice and canning, opened up new, inland markets for bivalve and shell products.

Bivalve habitats were not only harvested for their food value but also for their shells. These were used for landfill, road building, and construction, including large-scale burning for lime to create cement. Shells were also used for chemical production, soil conditioning, and fed to poultry. Between 1920 and 1944, 2.8 million t of shell products were produced from Chesapeake Bay oysters reefs (Hargis and Haven, 1999); of this over 1.5 million t were in the form of poultry grit and 1.2 million t of ground and/or burnt lime. In the gravel-poor coastal counties of Texas oyster shell was an important road building material, with nearly 30% of the more than 7.7 million cubic meters of oyster shell produced in Texas in 1955 alone going to road construction (Doran, 1965). In Australia, schooners supplying lime kilns simply berthed on oyster banks on low tide, then raked up live oyster and shell until the boat was full, a process referred to as “skinning” (Ogburn et al., 2007).

5. GLOBAL DECLINE OF BIVALVE HABITATS

Oysters and mussels fisheries have posed unique challenges for fisheries management because unlike fish and other mobile organisms, fisheries tend to simultaneously remove bivalves and their habitat. Larvae for many species preferentially settle on the shells of conspecifics so removing the habitat also reduces the available amount of suitable settlement substrate, thus limiting recruitment. The reef and bed structure is often bound together by the living bivalves. Once they are removed the physical structure of the reefs and beds are more vulnerable to being broken up by waves and currents. In addition, with the loss of vertical structure, remnant populations are more susceptible to smothering, predation, and disease.

Overfishing with destructive fishing gear is not the only driver of decline. There has been a long history of translocations and introductions of nonnative bivalves within and between bays and even countries in an attempt to revitalize struggling local fisheries (Beck et al., 2009; Gillies et al., 2015). All too often parasites, predators, and diseases were introduced with these relocations, or transported along with aquaculture gear. Severe disease and parasite outbreaks often followed these introductions driving native bivalve habitats to commercial and functional extinction in many coastal areas (Beck et al., 2009). While some native diseases were present their impacts were often exacerbated by a reduction in the vertical height of reefs and through increasing pollution, sediment, and nutrient loading in estuaries that could lead to decrease the resilience of shellfish to disease.

Peak harvest years were often coupled with rapid coastal land-use change and the clearing of local vegetation. This often led to large amounts of sediment entering estuaries and smothering bivalves. One example of this is evidenced in the wild oyster fishery of Rhode Island’s Pt. Judith Pond (United States). In the late 1930s, development expanded in this area. As a result, local dredging became intensive and sediment transport from these activities served as a catalyst in burying oysters in one of the most productive oyster fisheries in the region (MacKenzie et al., 1997). In other cases, such as Yaquina Bay, Oregon, pollution from the associated industries drove the decline of existing oyster beds (Fasten, 1931).

Many bivalve habitats in intertidal and shallow subtidal areas have been eliminated by coastal development activities including filling (“land-reclamation”) and dredging of shipping channels. In addition, reduced water quality and eutrophication have negatively affected many bivalve populations. Dam building and modification of water flow have also affected bivalve populations because many species have a relatively narrow range of salinity in which they thrive (Beck et al., 2009).

The catastrophic loss of bivalve reefs and beds is now well documented, along with the devastating consequences for local communities through loss of employment, food, and income security. Unfortunately, we are still managing the few remaining wild reefs without learning from past mistakes. Many oyster and mussel stocks are still being fished commercially using destructive methods despite being at less than 10% of their historical biomass (zu Ermgassen et al., 2012). Along with restoration the conservation of the last natural bivalve habitats should be a high priority for managers.

6. RESTORATION

Historically, restoration efforts have focused on fisheries enhancement with the goal of recovering lost or impaired bivalve fisheries. It is likely that people have translocated bivalves with them to establish easily accessible populations for millennia. There is a blurred line between fishing, local enhancement, and aquaculture. For instance, Native Americans in Rhode Island fished for oysters in deep waters of Rhode Island Sound, and then transplanted them to shallow areas in Pt. Judith Pond and Narragansett Bay for winter harvest.

Initial bivalve population recovery and restoration efforts included policies based around closed areas and closed seasons (Fig. 2). For areas where bivalve populations had collapsed, large-scale reintroductions were undertaken, sometimes between countries. For example, between 1894 and 1930, large amounts of spat (juvenile oysters) from the

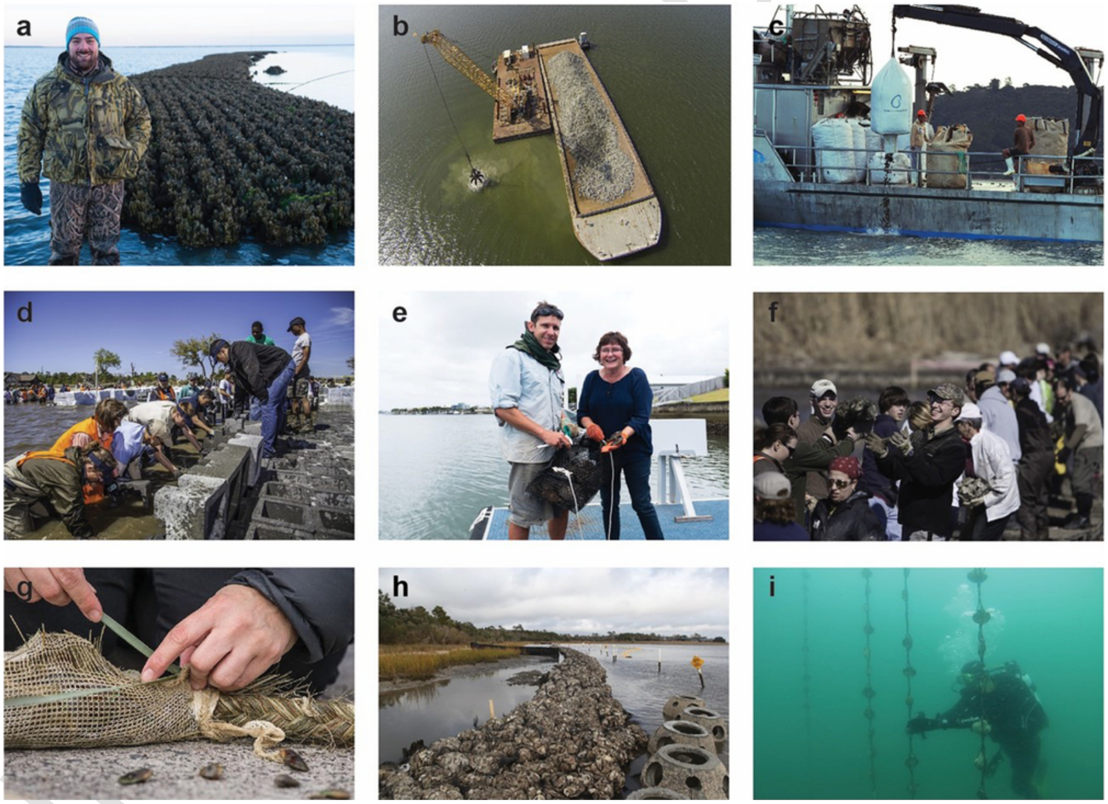

FIG. 2 Bivalve habitat restoration. (A) Constructed oyster bank using oyster castles. Virginia, United States. (B) Granite rock being deployed as oyster settlement substrate in the Piankatank River, Virginia, United States. (C) Live adult green-lipped mussels, *Perna canaliculus*, being deployed in to form beds in the Hauraki Gulf, New Zealand. (D) Volunteers assisting with oyster castle deployment, United States. (E) Oyster gardeners with oyster basket, Queensland, Australia. (F) Volunteers moving bags of oyster shells for intertidal oyster restoration, United States. (G)Traditional Maori flax weaving being used to create mussel settlement substrate, Auckland, New Zealand (H) Living shoreline in North Carolina with bagged oyster shell and reef balls deployed to provide a settlement substrate for oysters and to protect the shoreline from erosion. (i) *Ostrea angasi* spat being grown out on scallop shells prior to deployments in Port Phillips Bay, Australia. *(Photos from (A) I. McLeod. (B)US Army/Patrick Bloodgood. (C) Shaun Lee. (D) Erika Norteman/ The Nature Conservancy. (E) Ian McLeod. (F) Erika Norteman/The Nature Conservancy.(g) Shawn Lee. (h) Jackeline M. Perez Rivera, US Marine Corps photo. (i) Ben Cleveland.)*

Netherlands, France, and Norway were distributed in the North Wadden Sea to restore beds for commercial fishing (Gercken and Schmidt, 2014). In the early 1880s, vast numbers of rock oysters, *Saccostrea glomerata* were transplanted from New Zealand to Australia to restore their stocks (Ogburn et al., 2007). Moving oysters from Scotland to replenish English and Dutch stocks was also a common strategy in Europe (Thurstan et al., 2013; Gercken and Schmidt, 2014). Although these translocations were sometimes successful in supporting fisheries over the short term, they often created new problems. Often exotic diseases, competitors and predators were introduced along with the bivalves (Wolff and Reise, 2002). Another strategy was the broad-scale placement of shell or shell fragments at high densities on the seafloor to create a new settlement surface. This led to a large scale, and reasonably successful "put and take" fishery in the United States, where shell is laid down on the seafloor to catch spat, then the oysters are dredged up once grown, and the cycle is repeated (Schulte, 2017).

Since the 1990s, with a growing recognition of the ecosystem services provided by bivalve habitats, restoration efforts have started to focus on restoring reefs and beds for their structure and function (ecosystem services such as water quality improvements, shoreline protection and providing habitat, and food for harvested species) rather than just for their future harvest potential (Brumbaugh and Coen, 2009). Hundreds of bivalve restoration attempts have been made in the last three decades (Fig. 2; Kennedy et al., 2011). Restoration attempts have generally tried to overcome one or both of the two main limiting factors inhibiting natural recovery, substrate, and recruitment limitation.

Techniques used to restore populations limited by settlement substrate use shell or built three-dimensional reefs using rock or concrete. Attempts to restore populations with limited natural recruitment often included shells or other substrates seeded with juvenile oysters from hatcheries (Fig. 2). More recently there has been a focus on breeding disease-resistant bivalves for restoration efforts.

Unfortunately, most bivalve habitat restoration projects suffered from a lack of monitoring and poorly defined objectives. A review of available data on oyster restoration activities in the Chesapeake Bay in the period 1990–2007 found that few were monitored and the restoration project goals were often poorly defined (Kramer and Sellner, 2009; Kennedy et al., 2011). Many restoration projects were not protected from dredging leading to their failure (Schulte, 2017). Efforts to develop local and regional bivalve habitat restoration plans have been increasing in North America and Europe in recent times and guidelines have been provided such as that of Brumbaugh et al. (2006).

6.1 Large Scale Restoration Works

Recently successful bivalve restoration has been scaling up, particularly in the United States. This has been led top-down by large government initiatives and bottom up by community groups. In 2004, the US Army Corps of Engineers constructed a 42 ha oyster reef by placing dredged and washed oyster shells in Great Wicomico River, Chesapeake Bay. Schulte et al. (2009) reported the success of the project with 180 million oysters present, making this the largest wild oyster population in the world. The success of this restoration was attributed to the absence of dredge fishing and to the high vertical relief of the reefs, which mimicked historical natural reefs. The largest current initiative is the Chesapeake Bay Executive Order, which requires the oyster populations of 20 Chesapeake Bay tributaries to be restored by 2025. One of the target tributaries is Harris Creek, where between 2012 and 2016, 142 ha of oyster reefs were successfully restored, at a cost of US$28 million (Box 1: Case Study 1). In areas outside of North America, bivalve restoration has also been scaling up. For example, there are plans to construct 20 ha of *O. angasi* beds in South Australia over the next few years. There is little information about the scale of restoration efforts in Japan and China as projects in these countries are not well covered in the western literature. However, some bivalve restoration initiatives in these countries have been substantial. For example, Box 2 (Case Study 2) describes a project in China where 100 km of oyster reefs were constructed.

6.2 Community Restoration

Alongside large-scale often government-led restoration programs, community-led restoration is also scaling-up. Community-led restoration projects are usually relatively small scale and fall into three broad types, (1) oyster gardening of usually hatchery-produced oysters, (2) deployment of juvenile to adult bivalves within designated areas for stock enhancement, and (3) substrate enhancement using natural or recycled man-made materials, loose or in "bags" to enhance local settlement success (Brumbaugh and Coen, 2009). Such examples in Australia and New Zealand and in the United Kingdom are shown in Boxes 3 and 4, respectively. These initiatives are often led by citizen scientists (community, school, and Indigenous groups). Some of these programs are very large scale. In response to a lack of shell for restoration, shell recycling programs have started where shells are collected from restaurants and processing plants. One

BOX 1 Case Study 1: Large-scale Oyster Restoration in Harris Creek, Chesapeake Bay, United States

Author: Stephanie Reynolds Westby, NOAA

Historically, reefs of eastern oysters, *Crassostrea virginica*, supported extensive fisheries in Chesapeake Bay in eastern United States (Beck et al., 2011). Oyster restoration projects have been implemented in Chesapeake Bay for 30 years with the goals of restoring fisheries and ecosystem services. A recent state and federal policy called for a scaled-up approach, setting a goal of restoring oyster reefs in ten Chesapeake Bay tributaries by 2025. Resource managers and scientists collaboratively developed “Chesapeake Bay Oyster Metrics,” criteria defining restoration success at both the reef and tributary levels. Harris Creek (Fig. B.1) was selected as the first tributary for restoration because it is an oyster sanctuary with no commercial fishing allowed, shows historical evidence of large oyster populations, and has a remnant oyster population. State and federal partners collected data on benthic habitat and oyster populations, along with scientific and public input, and developed a plan to restore the reefs. Areas with shell benthic habitat and > 5 oysters per m^2 were treated with hatchery-produced seed oysters (spat-on-shell). Areas with no shell, or < 5 oysters per m^2 (around 50% of areas), were treated by constructing a reef base (0.3 m high, from stone or shell), followed by seeding. Target planting density was 12.5 million seed per hectare. Between 2012 and 2016, 142 ha of reefs were restored, at a cost of US$28 million. Reefs are monitored 3 years after restoration; reefs seeded in 2012 and 2013 (78 ha) have been monitored. All but 1.2 ha exceeded the threshold oyster biomass (15 g dry tissue weight per m^2) and density (15 oysters per m^2). Forty seven hectares exceeded the higher, target biomass (50 g dry tissue weight per m^2) and density (15 oysters per m^2). Stone-base reefs averaged four times higher oyster densities than shell-base reefs and shell-base reefs showed higher densities than seed-only reefs. The model developed in Harris Creek is being used for oyster restoration for other Chesapeake Bay restoration projects and may be modified for oyster reef restoration projects in other locations and countries.

Fig. B.1. Location of restored oyster reefs in Harris Creek. Funding was provided primarily from the National Oceanic and Atmospheric Administration, US Army Corps of Engineers, Maryland Department of Natural Resources, and Oyster Recovery Partnership.

of the most ambitious projects is the Billion Oyster Project which aims to bring 1 billion oysters back into New York City waters. Along with providing much of the person power and resources for restoration projects these initiatives also empower local communities through education and training. To support these initiatives and ensure efforts are likely to be successful best practice guidelines have been developed such as that of Brumbaugh et al. (2006).

BOX 2 Case Study 2: Oyster Restoration in China

Authors: Weimin Quan (Chinese Academy of Fishery Sciences, Qingdao, China) and Austin Humphries

Estuaries in China have an array of natural oyster (*Crassostrea ariakensis*) reefs as well as projects where active restoration methods are being tested, the most notable of which is at the mouth of the Yangtze River (Fig. B.2). In this urbanized setting where downtown Shanghai meets the coast, the Yangtze River was dredged for navigation purposes in 1997 and two ~ 50 km concrete dikes were constructed. In 2004, over 20 t of hatchery-reared seed oysters from Xiangshan Bay were transplanted by the East China Sea Fisheries Research Institute and thus constituted one of the largest restoration projects in the world at that time. Since then, results from our studies indicate that the restoration project was a success: the oyster population is self-sustaining with normally distributed size classes (Quan et al., 2012a); species diversity and abundance of resident macrofauna are high (Quan et al., 2009, 2012a); reefs supported higher trophic organisms than adjacent salt marsh areas (Quan et al., 2012b). Continued monitoring of this restored oyster reef will be necessary and important for determining temporal trajectories of ecological change (La Peyre et al., 2014), as well as improve our understanding of oyster reef dynamics in multiuse urban environment.

Oyster reef restoration is gaining interest and momentum in China as local stewardship increases, however, little mechanistic information is available to guide best practices under local conditions. One exception is a recent study that found many different types of substrate may be used for successful oyster recruitment, from clam and oyster shell to limestone and clay brick (Quan et al., 2017). These types of studies addressing specific mechanisms that mediate restoration success will be necessary to progress the science and practice in China. Additionally, questions remain about how oyster aquaculture may influence reef restoration and be better designed contribute to larval supply for restoration efforts.

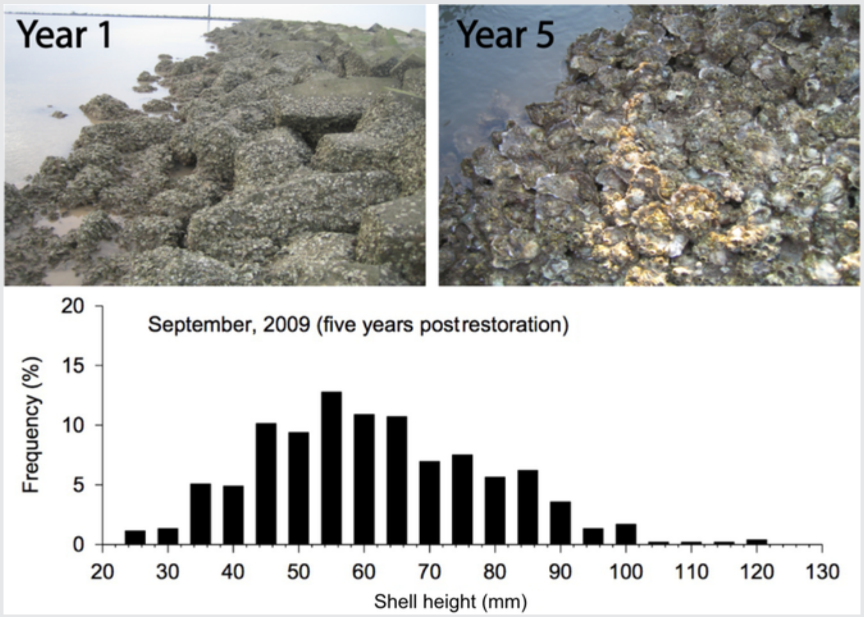

Fig. B.2. Restored oyster reef in the Yangtze River Estuary off the city shores of Shanghai, China. The concrete dike structure was built as part of a navigation channel project and then seeded with oysters (*Crassostrea ariakensis*) in 2004. The photo on the left dates from 2005, 1 year after the oyster restoration initiative, and the photo on the left was taken 5 years postrestoration. The graph below the photos shows the size distribution of oysters on the reef in 2009, indicating successful restoration with mature oysters.

(Modified from Quan, W., Humphries, A.T., Shen, X., Chen, Y., 2012a. Oyster and associated benthic macrofaunal development on a created intertidal oyster (Crassostrea ariakensis) reef in the Yangtze River estuary, China. J. Shellfish Res. 31(3), 599–610.)

6.3 Restoration for Coastal Protection

Coastal erosion is a growing problem internationally because of sea-level rise driven by climate change, and increasing population and development in coastal areas. Living shorelines that include living elements (natural infrastructure), such as salt marsh and oyster reefs are increasingly being considered as an alternative to “hard” or “gray” coastal protection measures such as bulkheads, revetments, and concrete seawalls that may displace energy causing further erosion nearby. Living shorelines can include sand, plants, logs, oyster shell (often in bags), organic materials (e.g., biologs made out of

BOX 3 Case Study 3: Bivalve Restoration Down Under (Australia and New Zealand)

Authors: Chris Gillies and Ian McLeod

Two of Australia's most prevalent reef-building species, the rock oyster (*Saccostrea glomerata*) and the flat oyster (*Ostrea angasi*), are now largely expatriated from estuaries and coastal embayments with fewer than 10% of reefs remaining (Beck et al., 2011; Gillies et al., 2018). Since 2014, several projects to restore rock and flat oyster reefs have been established near most major capital cities (Gillies et al., 2018). These projects are largely based on successful methods employed in the United States and follow recommend guidelines for ecological and reef restoration including laying down limestone structures subtidally and reintroducing adult oysters (e.g., Brumbaugh et al., 2006). Bivalve habitat restoration in New Zealand has focused on the large green-lipped mussel *Perna canaliculus* (hereafter mussels). Vast beds of mussels grew in estuaries around northern New Zealand. Beds were fished from 1300 km^2 of the Hauraki Gulf, outside of Auckland by dredging. The dredging was unsustainable and the fishery collapsed in the late 1960s. Fifty years later, beds have not recovered with less 1 km^2 remaining. Large-scale restoration experiments using adult mussels have shown that they can survive across their former range, but recruitment remains low and this is the focus of ongoing research. A non-for-profit group "Revive our Gulf" is driving much of the mussel restoration efforts in New Zealand with plans for scale-up and trials in other locations. Critical to the success of these initial projects are the strong partnerships developed with the bivalve aquaculture industry which provide emerging restoration practitioners with technical guidance on animal husbandry, reproduction and practical deployment. Equally important has been the support of recreational fishing groups whose values align strongly with common objectives of bivalve restoration such as increasing estuary productivity, improving water quality, and reinstating habitat for fish and crayfish (Fig. B.3).

Fig. B.3. Juvenile crayfish with *Ostrea angasi* oysters, Tasmania, Australia.

(From Cayne Layton.)

jute), concrete, material filled structures, or other recycled or natural structural material to provide shoreline protection. These dissipate energy, trap sediments to encourage the growth of plants such as salt marsh or mangroves and provide a settlement structure for oysters (the living components of living shorelines). Living shorelines may have lower installation and maintenance costs compared to fully engineered alternatives and have other benefits and services.

There is growing interest in using oyster reefs and living shorelines for coastal protection in places especially vulnerable to sea-level rise such as Bangladesh, the southern states of the United States, and the Wadden Sea. There was concern that oyster reef vertical growth may not be able to keep pace with sea-level rise. However, recent direct measurements by Rodriguez et al. (2014) has shown that reef height accretion for intertidal *C. virginica* is up to 10 times faster than previously estimated and intertidal reefs studied in the mid-Atlantic US estuaries should be able to keep up with predicted sea-level rise.

6.4 Should Nonnative Bivalve Species Be Used for Restoration?

Nonnative species of habitat-forming bivalve have been spread around the world. Many of these introductions have been deliberate in the attempt to restore depleted natural bivalve fisheries, or for aquaculture. Many other introductions have been accidental (transported on ships and equipment or in ballast water). These species can have positive or negative impacts on estuaries. Nonnative introductions have supported successful aquaculture industries in many countries. In the Wadden Sea the invasion of Pacific oyster, *Crassostrea gigas* has led to intertidal reef development that reduces coastal erosion and provides habitat for invertebrates (Herbert et al., 2016). In Australia, there have been no obvious negative consequences for the invertebrate communities as native *S. glomerata* reefs are replaced by *C. gigas* (Wilkie et al., 2012). However, the introduction of nonnative species has had devastating consequences for native bivalve species through the introduction of diseases, predators, competitors, and parasites (Wolff and Reise, 2002). Any future introductions should go through a rigorous risk assessment process that includes the risks to native bivalve species. https://link.springer.com/chapter/10.1007/978-94-015-9956-6_21.

7. THE FUTURE OF BIVALVE HABITAT RESTORATION

7.1 Social, Economic, and Environmental Benefits

The experiences from decades of restoration practice in the United States and elsewhere have demonstrated that bivalve habitat restoration can be a positive management action that results in multiple social, economic, and ecological benefits to estuaries and their surrounding communities. The restoration of bivalve habitats likely represents one of the few coastal habitats which have consistently achieved success at the “landscape-scale” across a variety of species, environmental conditions, and continents. One might ask why that has occurred for these systems and not for others? Perhaps part of the answer lies in the efforts of project proponents to emphasize the strong connection between community values and the social, economic, and environmental benefits derived from restoration such as job creation, livelihood benefits, and community economic benefits. Emphasis on communicating the social and economic benefits of bivalve habitat restoration enables communities to more easily align their own livelihood and wellbeing objectives with those of restoration proponents, thus enabling projects to receive support from a wider audience of diverse stakeholders rather than those focused solely on more narrow ecological (i.e., species recovery) benefits (Goldman and Tallis, 2009). Bivalve habitat restoration also provides communities the opportunity to collectively work on solutions to improve estuary health and coastal livelihoods rather than the more commonly divisive activities of problem definition and environmental regulation.

Key to the future growth of bivalve habitat restoration thus relies on the continued promotion of the natural and human benefits derived from the recovery of bivalve habitats in addition to the ecological benefits. Projects should consider the trade-off between setting purely ecological objectives (e.g., oyster specific metrics) against also including social and economic objectives such as job creation, community volunteering, and local business involvement. By documenting and communicating the social and economic benefits of projects in addition to ecological outcomes, economists, and estuary managers can more easily build the case for further investment in restoration activities and better assess trade-offs against investing in other social or environmental projects. Tools such as the oyster calculator produced by TNC (http://oceanwealth.org/tools/oyster-calculator) that allows managers to calculate how much oyster restoration is needed to reach water quality and fish productivity goals are likely to further build the case for sustained investments in bivalve habitat restoration. These initiatives also help to streamline objective setting, monitoring, and reporting across projects.

7.2 Global Expansion

Bivalve habitat restoration is on the cusp of expanding into new geographies such as Asia, Oceania, Africa, and Europe (where bivalve restoration is largely in the stages of early adoption [see case studies]). Partnerships between experienced organizations and early adopting organizations in new regions are an important step to scaling-up bivalve habitat restoration locally and globally. Such partnerships help transfer technical knowledge into new regions and expedite project development. They also provide opportunities for “knowledge donor” organizations to leverage their existing projects with new opportunities, resulting in a win-win scenario for both groups. Such partnerships also provide opportunities for global networks to strengthen and help build the foundation for global research, resourcing, and strategies. A global network of bivalve practitioners and researchers is likely to lead to stronger recognition of the role that restoration of bivalve (and other marine) habitats can play in meeting global development goals and international treaties. A global approach can also elevate the role that bivalve habitat restoration can play in helping to mitigate regional coastal threats such as pollution, coastal erosion, and ocean acidification, particularly around major coastal cities and communities.

7.3 Opportunities for Innovation

Like many habitat restoration projects, traditional project objectives have largely focused on recovering the primary habitat-forming species that was expatriated or degraded. Yet recent advancements in understanding ecosystem function, and thus ecosystem services, has helped expose a whole new range of possibilities for how habitat restoration can help address estuary threats and support livelihoods beyond just habitat loss. Estuary managers, communities, and coastal industries can now ask: what role can habitat restoration play in supporting commercial and recreational fisheries? How can bivalve habitat restoration support growth in the bivalve aquaculture industry? How can restoration help combat pollution and eutrophication or buffer shorelines from storm surges and sea-level rise?

BOX 4 Case Study 4: Essex Native Oyster Restoration Initiative

Authors: Philine zu Ermgassen, Sarah Allison (Essex Wildlife Trust) and Alison Debney (Zoological Society of London)

The River Blackwater has a long history fishing for the European native oyster, *Ostrea edulis*. Indeed, the *Colchester oyster* has been a sought-after delicacy for centuries (Sprat, 1669). In the 1800s *O. edulis* was overfished and impacted by poor water quality throughout its range, and since the 1980s from the introduced oyster disease, bonamia (Hudson and Hill, 1991). While the oyster fishery in the Blackwater persisted following the importation of broodstock, the fishery for the native oyster is now restricted to private grounds, with most oystermen focusing on harvesting the introduced Pacific oyster *Crassostrea gigas*. But the cultural heritage and fishermens' passion for the native oyster persists and it is the Blackwater Oysterman Association that has spearheaded the data gathering required to successfully designate the site a marine conservation zone for *O. edulis* habitat (beds) and the species, as well as the subsequent conservation efforts in partnership with conservation, industry and statutory bodies through the Essex Native Oyster Restoration Initiative (ENORI). Restoration work is being undertaken with three aims in mind: to recover the native oyster beds and species to self-sustaining levels as per the statutory conservation objectives, to restore the valuable ecosystem services provided by the native oyster, and to increase the oyster population to support the fishery of the species into the future. In 2015 25,000 adult oysters were purchased from the private fishery and re-laid in part of the public oyster grounds in the Blackwater Estuary to form a broodstock sanctuary. The relay site and surrounding area (totaling 200 ha) was voluntarily declared a no take zone within the estuary, which is more widely managed for the oyster fishery. This partnership and shared management approach is the first for this species in the United Kingdom. The laying of cultch and further broodstock enhancement is currently being planned in order to further restore the native oyster population (Fig. B.4).

Fig. B.4. *O. edulis* being deployed to restore populations in Blackwater Estuary.

(From Sarah Alison, Essex Wildlife Trust.)

BOX 5 Can Bivalve Aquaculture Replace the Lost Functioning of Bivalve Habitats?

Over the last five decades, aquaculture has become the fastest growing global food production sector (Diana, 2009; FAO, 2016). Bivalve aquaculture now dominates harvest from wild populations. For example, 95% of the world's demand for oysters is being met by aquaculture (Schulte, 2017). There are both synergies and conflicts between the goals of aquaculture and restoring lost bivalve habitats. Bivalve aquaculture requires high water quality and the bivalve aquaculture industry has helped improve water quality standards in many areas (e.g., through lobbying waste water treatment upgrades). The aquaculture industry also has vital bivalve husbandry knowledge and has developed disease-resistant stocks that are useful for restoration. Bivalve hatcheries that were primarily set up to produce spat (juvenile bivalves) for aquaculture are also needed to produce spat for large-scale bivalve restoration in recruitment limited systems.

Recently aquaculture has been considered as a potential tool to provide other ecosystem services. It has been suggested that bivalve aquaculture may provide a viable mechanism for reducing the eutrophication in estuaries as their role in improving water clarity and quality may be more powerful than natural reefs because of denser populations of bivalves. Lindahl et al. (2005) suggested that mussel aquaculture could provide a more cost-effective solution for reducing nitrogen in Swedish fiords than waste water treatment plants in some circumstances. Bivalve aquaculture provides habitat for many species of fish and invertebrates, and the benthic habitat below aquaculture facilities can be enhanced by the structured debris that falls from the aquaculture facility and the enriched biodeposits from bivalve filter feeding. However, at high densities bivalves can produce such a large quantity of nutrient-enriched biodeposits that the substrate below them becomes anoxic through bacterial decomposition rendering that habitat unsuitable for valued fish and invertebrate species.

Overall aquaculture can probably replace some, but not all the services provided by natural bivalve habitats, and the provision of services will be dependent on appropriate site selection. The biodiversity supported by aquaculture infrastructure and cultured bivalves is likely to be different from that of natural reefs, and aquaculture infrastructure is not likely to provide the same levels of coastal protection as natural reefs.

With the advancement and application of bivalve habitat ecosystem services, innovative, and long-term financing mechanisms can be established to support restoration expansion as a method to help manage and mitigate broader estuary (and associated livelihood) threats. For instance, the denitrification and phosphorus removal benefits derived from bivalve habitats (Newell et al., 2002; Kellogg et al., 2013; Humphries et al., 2016) could provide a nutrient sink mechanism with funding for restoration activities derived from estuarine nutrient trading schemes, sewerage or pollution offsets. Such programs could operate in a similar way to freshwater protection funds which divert funding from downstream management interventions (e.g., desalination plants) to fund upper catchment restoration projects in order to secure clean water. The fisheries production benefits of bivalve habitats (zu Ermgassen et al., 2016b) could provide a model for ecosystem-based fisheries management, whereby restoration activities are funded through recreational fisheries license funds or commercial seafood levies. The shared costs associated with developing bivalve hatcheries or research and development in bivalve genetics, disease, and husbandry could be paid for in part by restoration projects, with industry cost savings returned back to bivalve habitat restoration projects (Box 5).

With the advancement in learning and application of habitat function and ecosystem services, stronger global networks, and an emphasis on incorporating social and economic (in addition to ecological) objectives, the future of bivalve habitat restoration is set to continue to expand in the future. Large-scale habitat restoration projects can be understood by estuary managers, communities, and industry as a viable and cost effective option for mitigating several environmental threats while also helping to boost coastal livelihoods and industries reliant on healthy estuaries.

8. CONCLUSION

Bivalve habitats were once dominate dominant habitat types in temperate and subtropical estuaries and coastal waters, but are now greatly reduced over most of their former range. Given the important ecosystem services provided by bivalves this has contributed to the declining health of estuaries and the fisheries they support. In response to these declines, bivalve restoration is scaling up globally through large-scale government-led approaches and through small-scale local initiatives involving community groups and citizen scientists. Restoring bivalve habitats can improve the health of estuaries and coastal waters but is not a silver bullet. Restoration efforts will need to be coupled with improved management practices and the restoration of other habitat types such as seagrasses, salt marshes, and mangroves. Restoration of bivalves habitats is gaining support beyond conservation-focused groups with new projects focusing on food security, local employment, green engineering, shoreline protection, and nutrient trading. Estuaries will not be the same in the future with increasing coastal human populations and developments. Bivalve habitats of the future are unlikely to be restored to their historical extent and structure. However, we may able to recreate their historical functions and benefit from their ecosystem services through active restoration and by modifying aquaculture design, and incorporating bivalves habitats into coastal infrastructure planning.

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