CHAPTER 5
SHELLFISH REEF RESTORATION IN PRACTICE

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KEY POINTS

- **It is critical to understand whether the planned reef location is recruitment limited, substrate limited, or both. This will guide selection of restoration methods.**
- **Shellfish for planting onto restoration reefs may come from hatcheries, ponds, or local broodstock.**
- **Restored reefs can be constructed from various substrates. Choosing among these requires understanding local physical conditions as well as social and regulatory factors.**
- **Disease may be a factor in shellfish reef restoration, and should be understood prior to undertaking restoration.**

INTRODUCTION

Approaches to successful restoration vary with species, scale, and local biological, ecological, and physical conditions. Local regulatory and social factors are important as well. While it is useful to learn from national and international examples, it is also critical to think about how these may need to be adapted for application to a particular region or site. Understanding the physical attributes and basic functions of your local reference ecosystem (e.g. patch size, reef height, spawning time, oyster density, disease resistance, fish and invertebrate assemblages) will help to determine which technical approaches may need to be applied to restore the ecosystem. These can range from natural regeneration, through assisted regeneration to reconstruction approaches; all of which are preceded by the removal or mitigation of causal factors or threats. These different approaches can be largely summarised into whether a lack of reef substrate, lack of recruitment, disease, or a combination of these are preventing the natural recovery of the shellfish reefs.

IDENTIFYING THE APPROPRIATE RESTORATION ACTION

Typically, an area in need of restoration is either 'recruitment limited', 'substrate limited', or both (Brumbaugh and Coen 2009) and assisted regeneration or reconstruction methods would be required (Gann *et al.* 2019). Recruitment-limited environments lack sufficient nearby broodstock (mature, reproductively capable shellfish of the target species) to naturally populate existing reef structure. Substrate-limited environments lack reef structure to which shellfish larvae can attach.

The presence of abundant wild shellfish attached to docks, piers, pilings, seawalls, etc. near the proposed restoration site is a good indication that an area may be substrate limited but not recruitment limited. It is quite common for restoration sites to be *both* recruitment and substrate limited. Understanding whether the localised limitation is recruitment, substrate, or both will inform decisions on what restoration treatment should be applied.

Figure 5.1: Settlement plates deployed in Yung Shue O, Tolo Harbor, Hong Kong. Photo: Lori Cheung.

TECHNIQUES FOR ADDRESSING RECRUITMENT LIMITATIONS

In a recruitment-limited area, practitioners will need to add the target shellfish species to the reef. These can be adult animals, but more typically juvenile animals (often referred to as 'seed') are added. Juvenile shellfish tend to be more readily available in large quantities than adult broodstock; this is particularly true of the quantities required for large-scale restoration (i.e. 0.5 hectares or larger). If unsure whether your area is recruitment limited, one method of determining this is to collect data on spat settlement plates. Someone may have already done this, check with local academics, researchers or resource managers. If no information exists, the restoration practitioner can deploy settlement plates at a range of tidal elevations and check them monthly (Figure 5.1). This is best done for 1 or more years to understand seasonal peaks, but if time or resources are limited, at least put the settlement plates out during the anticipated spawning season (typically spring through late summer).

Sources for seed include hatcheries (juvenile shellfish production facilities), pond systems, and collection of wild spat on cultch (placing cultch in high-recruitment areas and transporting to the restoration site).

Hatcheries may produce either 'cultchless' seed (attached to very small pieces of cultch, such as a grain of sand or tiny shard of shell), or 'cultched' seed (seed – or several seed – attached to a larger piece of cultch, such as an empty shell). Cultched seed is most often used for restoration, as it tends to mimic the reef's natural structure, where larvae attach to shells produced by previous generations. Seed attached to larger cultch may also be less vulnerable to predation than small, cultchless seed. Cultchless seed is most often produced for shellfish farming, particularly where the animals will be grown in cages or bags and can be managed more easily as single oysters. A common type of cultched seed is 'spat-on-shell', where one or several juveniles are attached to a single, empty shell of the same species (Figure 5.2). Shell material may be obtained from commercial shellfish processing facilities or restaurants as part of shell recycling initiatives, but should be 'aged' in the sun for at least six months to ensure that pathogens are eliminated (see Chapter 4).

Hatcheries typically produce shellfish larvae, then place them in large tanks with water and cultch to allow the larvae to 'set' (attach) to the cultch. Some hatcheries may sell unset larvae. Unset larvae is far easier to transport than spat-on-shell (i.e., only a lime-sized ball of eastern oyster (*Crassostrea virginica*) larvae is required to set a 11,400-litre tank of spat-on-shell). Practitioners may be able to purchase the larvae directly from the hatchery, and set up a small remote setting facility to set the larvae onto cultch (Congrove *et al.* 2009). Remote setting techniques may vary by species. For example, mortalities have been 100% to date when attempting to transport European flat oyster (*Ostrea edulis*) larvae. Another promising technique is to release shellfish larvae to set directly onto a restoration site, where appropriate substrate is in place (Leverone *et al.* 2010; Fredriksson *et al.* 2016).

Annual production capacity at local hatcheries is another factor to consider. Hatcheries are typically structured to produce a set amount of product annually (seed, larvae, or a combination). They may have trouble meeting an increased demand with little or no advance notice. It is important to discuss project plans with the hatchery manager to determine the feasibility and timing of producing the required amount of product.

In Europe, pond systems are traditionally used to produce shellfish seed (Figure 5.3). Broodstock is placed in shallow, enclosed ponds, where temperatures rise sufficiently high for successful reproduction and natural phytoplankton supply. Cultch is placed in the ponds, and the broodstock produces larvae that set onto the cultch. Various cultch types, including artificial substrates and pre-fabricated reef structures, can be seeded in ponds. The cultched seed is then removed and transported to the restoration site.

Figure 5.2: Hatchery produced *Crassostrea virginica*, with spat on shell cultch in the front (red arrow) and mature oysters on shell cultch after a period of grow out. Photo: University of Maryland Center for Environmental Science, Horn Point Hatchery.

Figure 5.3: Ponds for seed production of *Ostrea edulis* in Cork, Ireland. Photo: Shmuel Yozari.

Relocation of natural (sometimes called 'wild') shellfish seed is another option for seeding reefs, and may be more feasible, cost-effective, and scalable than hatcheries (Southworth and Mann 1998). In this traditional technique, practitioners place cultch in a nearby area of high recruitment to catch naturally occurring larvae. The cultched seed is then relocated onto the restoration site. This technique works with the area's local broodstock and takes advantage of natural larvae. This method is used in many areas to populate private shellfish beds. It may be wise to consult with a local aquaculture specialist or shellfish biologist to find appropriate cultch placement locations and to understand local permitting issues.

Whether stocking from hatcheries, ponds, or relocation of natural seed, very high mortalities should be anticipated. This is the nature of placing very small animals onto a reef environment, and transportation and handling may increase mortality (see also Box 5.1). One large-scale restoration plan projected 85% mortality of hatchery-produced spat-on-shell in the first year, and 30% annual mortality thereafter (Maryland Oyster Restoration Interagency Workgroup 2013).

See Table 5.1 for examples of seeding densities on restoration reefs.

BOX 5.1: SHELLFISH REEF RESTORATION IN COLDER CLIMATES

If you are working where winter air temperatures drop below freezing (even only occasionally), and in a recruitment-limited area, be cautious about constructing intertidal restoration projects. Many shellfish species will freeze and die if exposed to freezing air temperatures. Mortalities will likely be near 100% with only one freezing incident (for example, an extreme low tide combined with freezing air temperatures).

As long as the structure persists, and there is sufficient local recruitment, this loss may be only short term as the reef can repopulate itself (Figure 5.4). However, if the area is recruitment limited, be aware that intertidal reefs may require constant re-seeding with the target species after each freezing to support a shellfish population.

Figure 5.4: Intertidal oyster reef in the southern Chesapeake Bay built from reef balls, pictured at mid tide level. Although winter temperatures here occasionally reach freezing, there is sufficient natural oyster recruitment to re-populate the reef when it experiences temperature-related oyster mortality. Photo: Stephanie Westby.

Table 5.1: Examples of seeding densities on shellfish restoration reefs in recruitment-limited areas.

REGION (REEF NAME)	SPECIES	JUVENILE OR ADULT ANIMALS?	INITIAL SEEDING DENSITY OF OYSTERS	TARGET OYSTER DENSITY POST RESTORATION
U.S. mid Atlantic coast (Chesapeake Bay, Harris Creek)	*Crassostrea virginica*	Juvenile	12.5 million per hectare	15-50 per m^2
Essex, UK	*Ostrea edulis*	Adult	3 per m^2	5 per m^2
North Sea, Netherlands	*Ostrea edulis*	Adult	10 per m^2	unknown
North Sea, Germany	*Ostrea edulis*	Juvenile	1 million per hectare	15-50 per m^2
Victoria, Australia (Port Phillip Bay)	*Ostrea angasi*	Juvenile	750,000 per hectare	50 per m^2
South Australia, Australia (Windara Reef)	*Ostrea angasi*	Juvenile	350,000 per hectare	50 per m^2

Shellfish gardening programs (where individuals grow shellfish off docks in floats or cages for planting onto restoration areas) can be a source of adult broodstock for small-scale restoration projects (Figure 5.5). If such programs already exist locally, check with program operators about obtaining animals for the planned reef. If no program exists, practitioners can start one, recognising that the shellfish for the gardens still needs to come from hatcheries, ponds, or relocation of natural seed.

Oyster gardening can increase local broodstock, which may provide a larval supply in otherwise recruitment-limited systems (Brumbaugh *et al.* 2000a,b).

A further advantage of oyster gardening is that it engages the local community in reef restoration and can provide hands-on educational experience. In areas where reefs are largely subtidal, such as Europe, this can be one of the few ways in which the community can engage with the target restoration species.

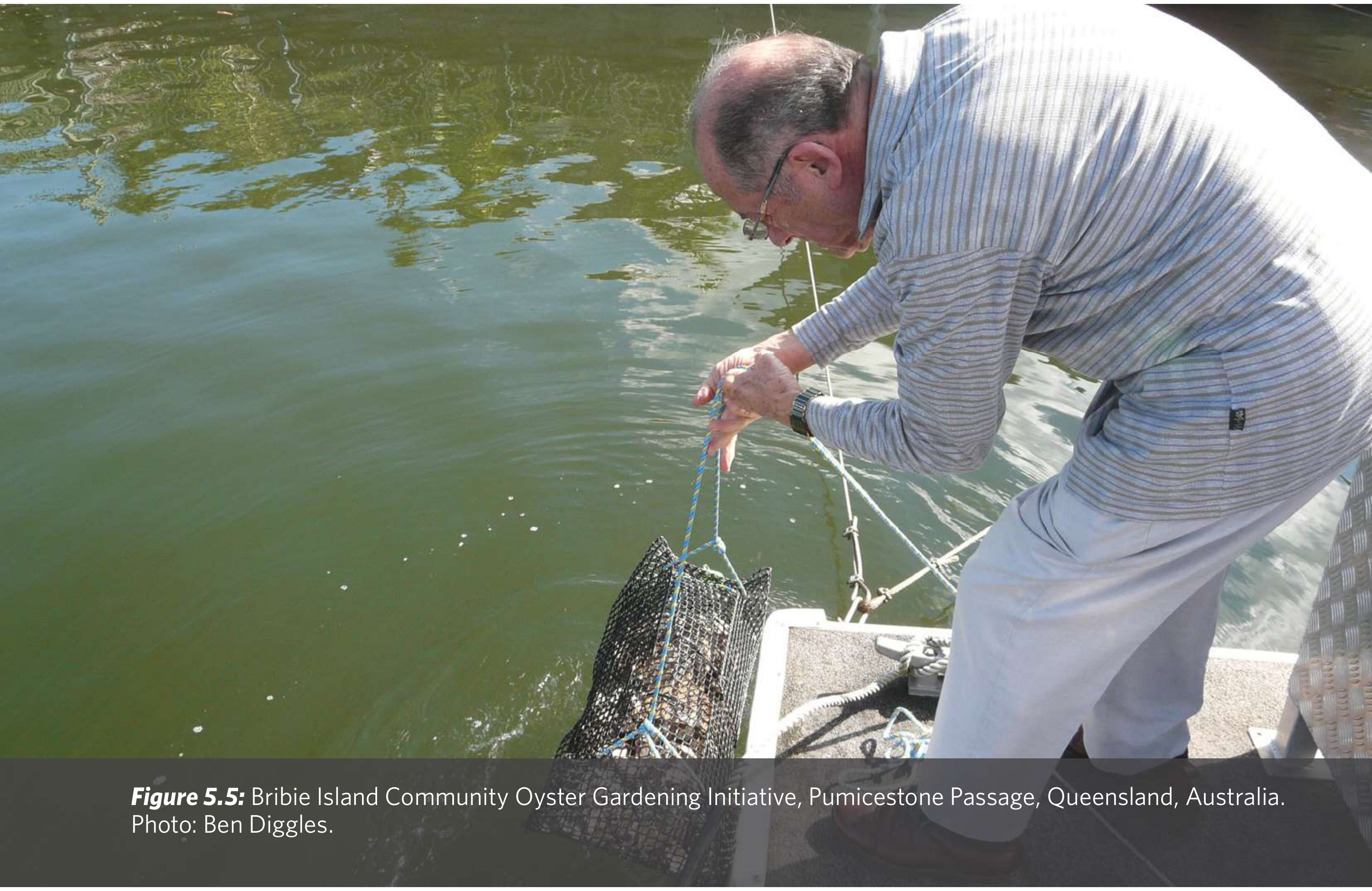

Figure 5.5: Bribie Island Community Oyster Gardening Initiative, Pumicestone Passage, Queensland, Australia. Photo: Ben Diggles.

TECHNIQUES FOR ADDRESSING SUBSTRATE LIMITATION

In substrate-limited areas, practitioners will need to construct reefs from some type of appropriate substrate (Figure 5.6). (If the area is both substrate- and recruitment-limited, practitioners will need to construct reefs, then seed them with juvenile oysters, as described above).

Selecting reef-building substrate requires careful consideration of the local biotic and abiotic environment, social factors, and material availability. A literature review is available on substrate materials used in the USA including porcelain, concrete, stablised coal ash, stone, shell, and engineered structures (NOAA 2017). Table 5.2 lists costs for some materials that have been used for projects in the USA, Europe, Hong Kong, China and Australia.

Figure 5.6: Barge deploying shell and stone to restore shellfish reefs as part of the Elizabeth River Project, Chesapeake Bay, USA. Photo: Joe Rieger.

Factors to consider when selecting reef material include:

- **Recruitment:** Will the target shellfish species set on the selected reef material?
- **Wave energy:** Higher-wave-energy areas typically require larger, more durable, heavier reef-building substrate to ensure durability.
- **Water depth:** Will the shellfish reef be subtidal (submerged at all times, even at extreme low tides), or intertidal? Intertidal reefs may be affected by even low amounts of surface wave energy, and must be constructed to withstand it. Shallow subtidal reefs may also be affected by surface wave energy. Reefs constructed from lightweight materials (shell, small stone) may spread out and lose three-dimensionality or disappear entirely.
- **Benthic characteristics:** Heavy reefs may sink in soft mud, whereas shell or other hard bottom substrate may be able to support the weight of the reef.
- **Purpose of the reef project:** For example, if the reef is to provide shoreline erosion protection, it needs to be constructed from materials that can serve that function.
- **Sedimentation:** If the reef is in a high sediment accumulation area, it should be constructed with greater relief to withstand those conditions. Ideally select a low sediment accumulation area instead.
- **Sanctuary status and public health:** Is shellfish harvest allowed in the area? Does the selected reef material allow for harvest, or prevent it? If the area is closed to shellfish harvest due to human health concerns, will the material help protect it from illegal harvest?
- **Fishing gear restrictions:** Is bottom trawling allowed in the area? Does the selected material harm fishing gear, or prevent fishing?
- **Conservation status of the restoration site:** Does the selected reef material and reef design comply with conservation designations (e.g. marine protected area; sanctuary status; historic designation)? It may be wise to consider potential natural movement of reef material, and how that might affect nearby protected areas or features.
- **Public and regulatory acceptance of the material:** Materials considered natural (e.g. shell, stone, clay) may have greater public and regulatory acceptance than others (e.g. slag, concrete, recycled porcelain, plastic), but local opinions can vary widely. It is critical to consult with the regulatory agencies, local community, and stakeholders to determine preference.
- **User group conflicts:** Will the reef material interfere with (or enhance) recreational or commercial fishing – either for the target species or other species? Will it interfere with boating or the view from shore? Even if the shellfish reefs once occurred there, current users may be accustomed to or prefer the way the ecosystem looks or functions now.
- **Reef material acquisition and placement:** A particular material may be well suited for a site, but locally unavailable. Material costs, transportation costs, and logistics must be considered. Substrate may be placed by hand (where safe) for small amounts of lightweight material in shallow water, or require cranes and barges for large amounts of heavy material in deep water.
- **Material cost:** material cost can vary widely (see Table 5.2 for examples).

There may be a strong seasonal component to addressing both recruitment and substrate limitations: hatcheries and ponds may only produce seasonally; natural set may only occur seasonally; and substrate reefs designed to catch naturally occurring larvae may become fouled with non-target species if placed out of sync with the target species' spawning cycle. It may be useful to consult on seasonality with a local fisher, or a shellfish biologist from an agency, non-government organisation, or academic institution.

Deployment of Lau Fau Shan shellfish reef, Hong Kong. Photo: Kyle Obermann.

Table 5.2: Costs for recent shellfish reef restoration projects. These costs are for reef material (substrate) purchase and placement only; they exclude costs for planning, design, permits, and cost for planting seed onto the reef.

SPECIES	PROJECT NAME AND REGION	REEF SIZE (HECTARES)	REEF HEIGHT (M)
Crassostrea virginica	Harris Creek, Chesapeake Bay, US East Coast	Various, 0.4 to 4.8 per reef; total of 30 hectares (additional reefs were built in Harris Creek using other materials)	0.3
Crassostrea virginica	Piankatank River, Chesapeake Bay, US East Coast	10	0.46
Crassostrea virginica	Piankatank River, Chesapeake Bay, US East Coast	6	0.15
Crassostrea virginica	Biloxi Bay, US Gulf of Mexico	0.01	1.1
Ostrea edulis	Blackwater, Crouch, Roach and Colne Estuaries, Essex, UK	0.12	0.3
Ostrea edulis	Borkum Reefground, German Bight, North Sea	0.04	0.3-1
Ostrea angasi	Margaret's Reef and Wilson Spit, Port Phillip Bay, Victoria, Australia	2.5	0.3-1
Ostrea angasi	Windara Reef, Gulf St Vincent, South Australia, Australia	20	0.7-1
Crassostrea ariakensis, Crassostrea sikamea	Sanmen Reef, Zhejiang, China	1	1
Crassostrea honkongensis	Lau Fau Shan Reef, Deep Bay, Hong Kong	0.06	0.3
Mixed shellfish that will recruit naturally (likely *Crassostrea bilineata* and *Perna viridis*)	Yung Shue O Reef, Tolo Harbor, Hong Kong	0.0015	6

* A collaboration between the Zoological Society of London, The Nature Conservancy, University of Essex, University of Edinburgh, Natural England, Cefas, Environment Agency, Tollesbury and Mersea Oyster Company, Colchester Oyster Fishery, Kent and Essex Inshore Fisheries and Conservation Authority, Essex Wildlife Trust, River Roach Oyster Company and Blue Marine Foundation.

REEF MATERIAL	REEF LOCATION (NEARSHORE/ ESTUARINE; OFFSHORE)	US$ PER HECTARE (MATERIAL COST + PLACEMENT COST)	ACTUAL REEF FOOTPRINT** POST RESTORATION (PER HECTARE)	REEF CONSTRUCTED BY
Stone, 7 cm to 15 cm diameter, and conch, clam and scallop shell	Nearshore/ estuarine	$235,000	100%	U.S. Army Corps of Engineers (federal agency)
Stone, ave 30 cm diameter	Nearshore/ estuarine	$200,000	40%	U.S. Army Corps of Engineers (federal agency)
Stone, ave 5 cm diameter	Nearshore/ estuarine	$37,500	100%	The Nature Conservancy and Virginia Marine Resources Commission (state government)
Oyster Castles (pre-fabricated concrete structures)	Nearshore/ estuarine	$2,400,000	33%	The Nature Conservancy
Mix of stone and shell (scallop and cockle)	Nearshore/ estuarine	$217,235	100%	Essex Native Oyster Initiative
stone, mixed shell, 3D-printed sandstone	Offshore	$570,000	75%	Alfred Wegener Institute, Federal Agency for Nature Conservation*
Limestone, ave 40 to 50 cm diameter and mixed shell	Nearshore/ estuarine	$85,000	15%	The Nature Conservancy
Limestone, ave 20 cm diameter	Nearshore/ estuarine	$123,700	6%	The Nature Conservancy
Stone, 10 to 40 cm in diameter	Nearshore/ estuarine	$8,555	0.8%	The Nature Conservancy, and East China Sea Fisheries Research Institute
Rough concrete posts	Nearshore/ estuarine	$85,690	10%	The Nature Conservancy
Recycled shell	Nearshore/ estuarine	$3,427,000	100%	The Nature Conservancy

** Some reefs were constructed by completely covering the reef footprint with substrate. These are denoted by '100%' in this column. Other reefs were constructed by placing reef material over a certain percentage of the reef footprint, for example in a striped configuration. These reefs are denoted in this column by a percentage less than 100.

TECHNIQUES FOR ADDRESSING SITE SELECTION

Practitioners should keep in mind that a successful reef location is one that meets *both* the biological needs of the target species *and* the interests of the local human community (e.g. acceptability of reef material, user group conflicts, regulatory compliance). Siting a reef based on only one or the other may reduce the potential for project success. The parameters used to determine reef site overlap with those used to determine reef material (see bulleted list above, 'Factors to consider when selecting reef material').

Additional parameters to consider when siting a shellfish restoration project include:

- **Historic presence of the target shellfish species:** seek evidence that the target shellfish species existed in the area historically. This can be historic maps or data sets, or evidence of shell substrate at or near the site.
- **Water quality:** determine if the area has suitable dissolved oxygen, temperature and salinity to support the target species. This information may be available from local academics, watershed groups or government.
- **Water depth:** carefully determine whether an intertidal or subtidal location is preferable, particularly in areas where air temperatures can fall below freezing (see Box 5.1). This may also influence reef material selection. Consider potential conflicts with local navigational channels and boat traffic when determining where and how tall to build the reef.
- **Biotic factors:** seek information from researchers or resource managers regarding food availability for the target species and predation issues.
- **Overall feasibility:** consider reef material availability, transportation, logistics, public acceptance, regulatory framework, harvest status for the target species and other species, and user group conflicts.

PILOT PROJECT

Once the site has been selected, the next stage of restoration can involve a pilot or proof of concept project, to learn empirically if a shellfish restoration project will work in a given location. Pilots are small-scale projects (typically from 10s of square meters to 0.5 hectare), with scale being the main difference between these and full-size projects. A pilot should go through the same feasibility, design, planning, public consultation, permitting, construction, and monitoring as a larger project. The pilot should be monitored to determine not only the health of the reef and target species, but for any additional services that are stated as goal of the larger restoration effort.

TECHNIQUES FOR ADDRESSING SHELLFISH DISEASE

In this section we discuss diseases that affect the health and survival of shellfish. These diseases may not be harmful to humans consuming them. However, some infections carried by shellfish (e.g. *Vibrio vulnificus*, toxic microalgae, Salmonella, Shigella, and toxin-forming bacteria) may not harm shellfish, but are harmful to humans consuming them, especially raw. Certain diseases can cause substantial mortality in shellfish populations, including those inhabiting restoration projects. Some common shellfish diseases include *Bonamia*, *Marteilia*, dermo, Herpes, Winter Mortality Disease, Queensland Unknown (QX), Juvenile Oyster Disease and Multinucleated Sphere Unknown (MSX). They are induced by protozoans, bacteria, or viruses, and may affect different life stages of shellfish. The movement of shell or living shellfish for restoration purposes should therefore consider this potential threat (see Chapter 4 on biosecurity for more guidance). There are no examples of diseases being eliminated once they are present in a system. Therefore, where diseases are already present in the restoration area, restoration can take either a passive or an active approach as described below.

LIVING WITH DISEASE

One approach to disease is to simply 'let nature take its course'. That is, proceed apace with restoration work, with the understanding that some, many, or even most, of the individuals on the site may succumb to disease. The theory behind this is that: a) it may not be possible, with existing knowledge and practices, to reduce disease pressure, and b) the disease may cause the weaker, less-tolerant individuals to die off, leaving the more-disease-tolerant individuals to produce future (hopefully more disease-resistant) generations. This approach also allows for selection of other traits which may afford increased growth or survival on the basis of local conditions. Under this scenario it is preferable to use local, previously exposed broodstock in restoration activities (see Chapter 4). Although this idea is theoretical, supporters in the scientific community believe that the shellfish that do not succumb to disease – even if there are very few – are actually the most valuable in terms of developing population-wide disease tolerance.

A further consideration when choosing the approach of 'living with disease' is to consider the other stressors that may impact on the shellfish population. For example, while the disease *Bonamia* can result in significant mortalities, the prevalence of the disease in an infected population appears to vary greatly with stress (van Banning 1991; Lynch *et al.* 2005).

Stressors may include: transplanting/handling; suboptimal salinity or temperature; low food availability; or high oyster density. Considering how these stressors can be reduced and hence allow the oyster population to recover despite the presence of disease is a further theoretical consideration, and not sufficiently understood so far.

DISEASE RESISTANCE

A tremendous amount of work in disease-prone but important oyster growing areas has been done to develop genetic lines that are resistant to disease (Dégremont *et al.* 2015). Most of this work has focused on improving industry productivity, but restoration practitioners can also take advantage of these improvements. Use of disease-resistant strains, however, would require practitioners to use hatchery-bred spat. There are several important factors to consider regarding use of disease-resistant spat. The most disease-resistant genotypes in one environment will not necessarily be the most resistant to the same disease in another environment. Developing a genotype resistant to one disease is not likely to confer resistance to other diseases; however, it is possible to simultaneously select for resistance to two diseases. Development of disease-resistant strains requires a dedicated program with facilities and a consistent level of support. Disease-resistant native oyster genotypes have been developed for restoration areas along the East Coast of the USA and in Australia (Dégremont *et al.* 2015).

Macroparasites in shellfish (e.g. copepods and trematodes) may not always cause epidemic diseases or severe threats to the population. They can be undesirable in aquaculture for aesthetic reasons, but if not harmful to the target species they can be considered as part of the natural ecological species community in restoration. In other cases, trematodes have been documented to cause substantial oyster mortality (Hine and Jones 1994).

TECHNIQUES FOR ADDRESSING SPECIFIC ECOSYSTEM SERVICES

Ecosystem services can often be used to set restoration objectives. If restoration projects address a specific set of ecosystem services, the approach, technique and scale need to be adapted accordingly, for example for:

- **Shoreline protection/living shoreline:** Reefs are constructed in intertidal areas. Ideally, they enforce marsh grass habitats, are a link to sublittoral habitats and will grow with sea-level rise. Construction needs to withstand higher wave energy compared to sublittoral sites. Shellfish/target species needs to be adapted to the intertidal areas.
- **Filtration capacity/water quality:** For maximum filtration rates, reefs are constructed in sublittoral areas. The volume of water cleared per oyster depends on species, size, sediment load, temperature, salinity and time submerged (zu Ermgassen *et al.* 2016). Nitrogen removal and carbon sequestration are additional gains. For further information see https://oceanwealth.org/tools/oyster-calculator.
- **Biodiversity/fish enhancement:** Reefs are constructed as complex three-dimensional habitats to maximise structure and area for invertebrates and fish to settle, to hide, to find food, and to spawn. For further information on quantities of fish increase per area of restored reef in the USA, see https://oceanwealth.org/tools/oyster-calculator.
- **Oyster fishery/harvesting:** Reefs are constructed in substrate-limited areas, e.g. by providing suitable substrate/cultch for successful recruitment. Oyster harvesting will mean substrate/cultch has to be renewed on a regular basis.

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