Mudflat Aquaculture

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Chapter 14
Mudflat Aquaculture

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Contents

Abstract It was probably an easy and inevitable transition from mudflat fishing to mudflat aquaculture in prehistoric times. Historical references date from the first century AD, and mudflat aquaculture is now practiced worldwide. Culture consists primarily of infaunal and epifaunal bivalve species, with the Manila clam (*Tapes philippinarum*), followed by the Pacific oyster *Crassostrea gigas,* as the most important species worldwide. In this chapter, production statistics and rearing practices are reviewed, and placed in context with environmental issues.

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1 Historical Context

It is difficult to ascertain when mudflat aquaculture actually began, because without archaeological evidence (e.g. vestiges of barriers), wild-fished bivalve shells in prehistoric middens cannot be distinguished from wild-fished juveniles which were then re-seeded in protected plots on the mudflat. Evidence of such ‘transitional’ mudflat aquaculture has been documented in North America from the first century AD (Lepofsky et al. 2015; Jenkins 2017). The *vivarae piscinarae* which appeared, beginning in the first and second centuries AD, and which were an integral part of the estates of wealthy Roman nobles, may have contained shellfish (Nash 2011). However, the undisputed presence of husbanded marine shellfish dates from the third or fourth century AD, with the depiction of a labelled ‘*Ostrearia’* on a blown glass bottle (Günther 1897; Fig. 14.1). By the thirteenth century on the French Atlantic coast, mussel spat began to be caught on wooden stakes between which a network of branches were strung, giving rise to the ‘bouchot’ tradition which has continued, in modified form, to this day. The Japanese began to use a similar system for capturing oyster spat on bamboo poles during the Shogun period beginning in the thirteenth century. By the nineteenth century, juveniles were being reared in net bags attached to the poles, increasing the production per pole. With the development of the hanging-culture technique in the 1920s, bivalve aquaculture was able to expand beyond the mudflats to the sublittoral zone (Nash 2011).

Official interest in European shellfish aquaculture on mudflats increased with the work of Professor Coste in France in the nineteenth century, who developed the technique of capturing oyster spat on modified ceramic roofing tiles. It was at this time (the ‘Second Empire’, 1852–1870) that Emperor Napoleon III decreed the creation of two Imperial Oyster Parks in Arcachon Bay, which has remained a major site of oyster production to this day (Nash 2011). Mudflat culture of oysters, clams, and mussels increased steadily throughout the twentieth and early twenty-first centuries, both in Europe and the New World, despite recurrent epizooties among the oyster populations and, more recently, the Manila clam populations.

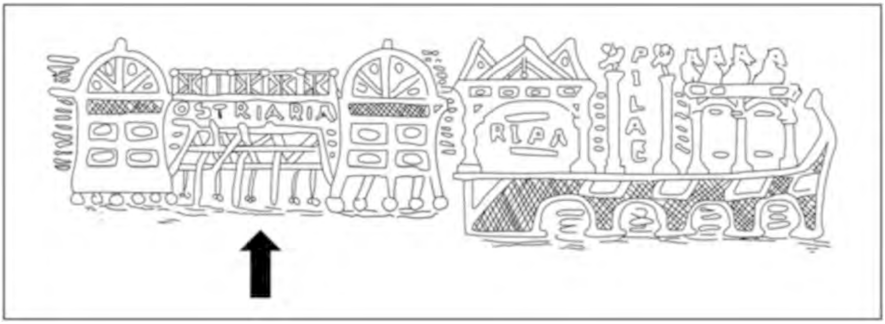

Fig. 14.1 Line drawing from the Roman ‘Populina Bottle’, dating from the third to fourth century AD. Note the ‘*Ostrearia*’ for rearing juvenile oysters to adults. The slight difference in spelling may be the artist’s mistake, or an accepted variation; despite the impressions of many students, Latin was a relatively fluid language. Redrawn from Günther (1897).

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2 Major Taxa Reared: Endobenthic (Clams, Cockles) and Epibenthic (Mussels, Oysters)

The major taxa reared (i.e. those for which a declared world production is $\geq 3 \times 10^5$ metric tons) are oysters, clams, and blood cockle (which is in fact an arkshell), of which by far the dominant species are *Tapes philippinarum*, *Crassostrea gigas*, and *Tegillarca granulosa*, respectively (Figs. 14.2, 14.3, 14.4 and 14.5). All three species grow quickly under mudflat conditions, and are accustomed to regular tidal exposure.

In addition to these three dominant species, mussels (*Mytilus* spp.) are important cultured species in some countries, e.g. France and the Netherlands; in both

Fig. 14.2 Basket of Littleneck (= Manila) clam, *Tapes philippinarum*, showing the great degree of heterogeneity in shell pigmentation. Photo PG Beninger.

Fig. 14.3 Pacific oyster, *Crassostrea gigas*. Photo PG Beninger.

Fig. 14.4 Blood cockle, *Tegillarca granulosa.* Note the bright red mantle pigmentation due to the presence of the hemoglobin respiratory pigment. Photos S. Shumway.

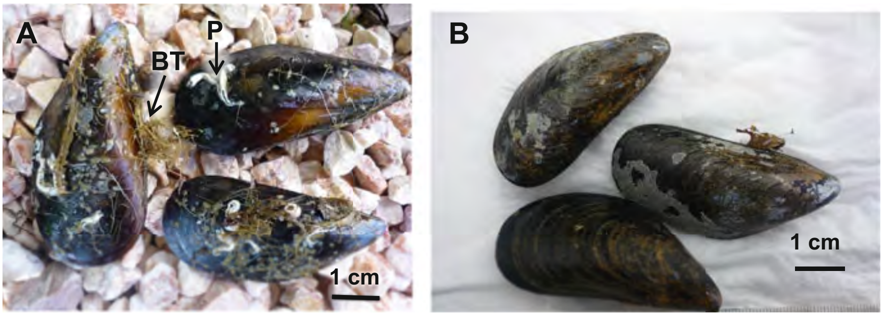

Fig. 14.5 Mussels, *Mytilus spp.* (**a**) Wild-caught *Mytilus edulis*, showing byssus threads (BT) and epibionts such as serpulid polychaetes (P). (**b**) Cultured *Mytilus galloprovincialis*, showing few epibionts (bryozoan *Flustra* sp.). Photos PG Beninger.

countries, the link to the mudflat is indirect, since in the Netherlands only the broodstock are protected on the mudflat, and in France the bouchot culture is either on more sandy substrate in the intertidal, or below low-water mark on muddy sediments. The northern quahog *Mercenaria mercenaria* and the cockle *Cerastoderma edule* are also important local mudflat-cultured species.

3 Global Production and Value

The global aquaculture production and value of the dominant mudflat species are shown in Tables 14.1 and 14.2. The aggregate category of infaunal bivalves 'Clams, cockles, arkshells' leads in both production and value, at 5,360,280 metric tons and USD 5,352,922, respectively, in 2014. The epibenthic oysters follow, with 5,155,257 metric tons and USD 4,174,258, respectively. The aggregate category of 'mussels', which includes *Mytilus* spp., *Perna* spp.,and *Aulacomya* spp., has a

Table 14.1 World aquaculture production of intertidal bivalves, 2005–2014

Species group			2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
53	Oysters	Q	4,155,840	4,312,197	4,402,618	4,144,379	4,309,291	4,489,002	4,503,836	4,727,722	4,951,880	5,155,257
		V	2,859,899	2,965,131	2,963,478	3,272,369	3,341,686	3,604,936	3,828,020	3,856,475	4,090,723	4,174,258
54	Mussels	Q	1,718,513	1,659,132	1,598,339	1,585,316	1,729,425	1,806,557	1,877,781	1,828,116	1,768,129	1,901,962
		V	1,044,899	1,195,219	1,627,854	1,629,202	1,516,764	1,592,661	2,310,101	2,201,240	3,352,803	4,070,629
56	Clams, cockles arkshells	Q	3,677,841	3,903,823	4,202,065	4,364,985	4,454,119	4,887,543	4,926,407	4,999,075	5,163,552	5,360,280
		V	3,418,954	3,762,954	3,978,820	4,266,420	4,361,591	4,777,884	4,923,933	4,953,620	5,170,635	5,352,922

Species group 56 is predominantly infaunal species (clams, cockles, and arks—the latter also called cockles in Asia) yet inhabiting predominantly sandy sediments or even the epibenthos, and species groups 53 and 54 are epibenthic species (oysters and mussels), which may also be reared in the sublittoral. Some clams can/are also cultured in the sub-tidal, e.g. *Mercenaria*). *Q* quantity in metric tons, *V* value in USD. Note the steady increase in tonnage, with the exception of mussels, and the steady increase in value for all groups. Source: ftp://ftp.fao.org/FI/STAT/summary/b-1.pdf

Table 14.2 World aquaculture production from 2006–2014 of the three top-ranking cultured bivalve species

Species		2006	2007	2008	2009	2010	2011	2012	2013	2014
Tapes philippinarum	Q	2,807,042	3,045,702	3,110,042	3,249,381	3,604,232	3,676,394	3,786,908	3,896,746	4,010,703
	V	2,965,131	2,786,579	2,877,917	3,041,365	3,353,406	3,478,337	3,546,820	3,644,762	3,744,222
Crassostrea gigas	Q	697,155	728,436	640,020	645,144	652,183	616.745	607,808	552,665	625,925
	V	962,132	971,575	1,156,293	1,128,710	1,222,870	1,397,473	1,283,217	1,321,997	1,343,591
Tegillarca granosa	Q	394,171	413,173	419,299	427,205	465,871	404,896	389,850	450,957	451,446
	V	420,311	4 54,264	466,540	462,657	510,901	483,602	478,526	566,523	580,260

Q quantity in metric tons, *V* value in USD. Source: http://www.fao.org/3/a-i5716t.pdf

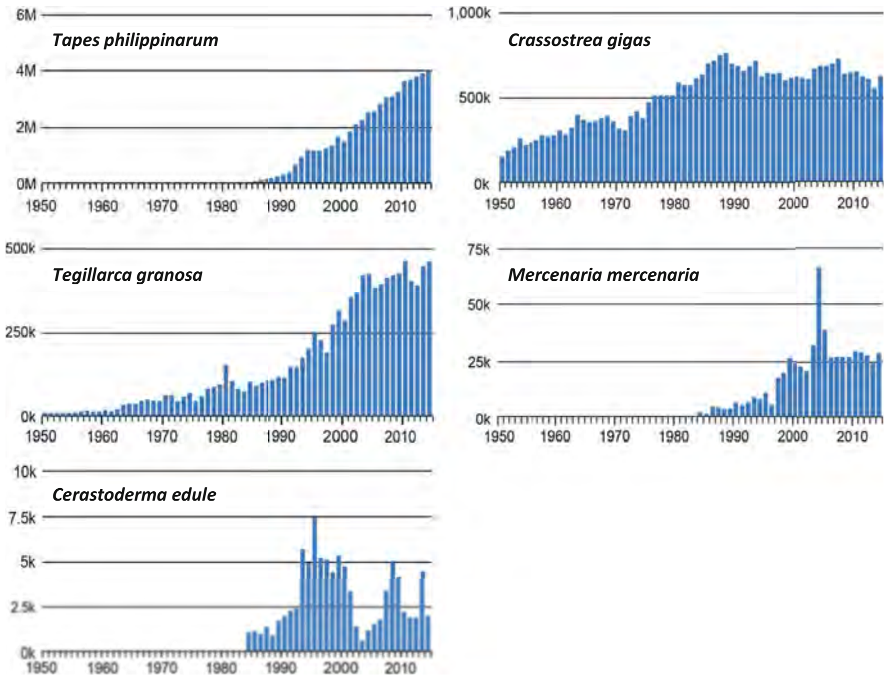

Fig. 14.6 World aquaculture production for species usually grown on mudflats. k = 1000 metric tons, M = 10^6 metric tons. Re-drawn from http://www.fao.org/fishery/species/search/en.

combined production and value of 1,901,962 metric tons and USD 4,070,629, respectively, representing a much greater value per kg than the oysters. It is of course difficult to distinguish between intertidal and subtidal aquaculture production of oysters and mussels without resorting to more local statistics; the same is true of species with a production $<3 \times 10^5$ metric tons, as is the case with the 'mussel' category, since they are all merged in this single category, despite the fact that some, such as *Aulacomya* spp., are mostly grown on floating lines in the subtidal zone.

From Table 14.2 and Figs. 14.6 and 14.7, it is evident that all three of the top-ranking cultured bivalves worldwide are primarily mudflat species (*Tapes philippinarum*, *Crassostrea gigas*, *Tegillarca granosa*). In terms of both tonnage and value, cultured *T. philippinarum* is by far the top-ranking bivalve compared to all other fished and cultured bivalves in the world. The culture of *T. philippinarum* began as the fishery production declined in the 1990s, and was immediately successful, outstripping fishery production in the mid-1990s; in 2002, 97.4% of world production was carried out in China alone. In Europe, the most similar native cultured clam species, *Ruditapes decussatus*, is now a minor product, although gastronomically appreciated (especially in Spain and Portugal).

The second-ranking mudflat-cultured species, *Crassostrea gigas,* has been introduced for successful aquaculture around the world (Fig. 14.12), such that culture production now dwarfs the very low and irregular wild fishery capture (Fig. 14.13).

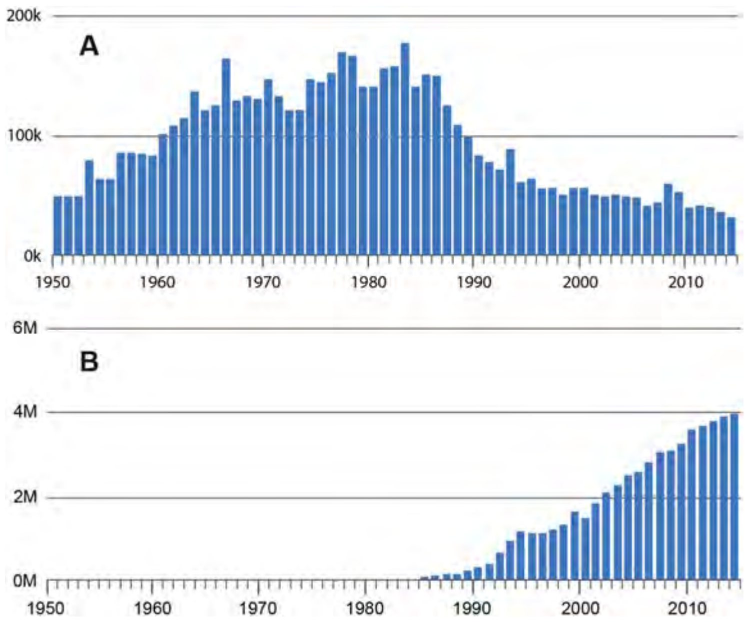

Fig. 14.7 *Tapes philippinarum*. (**a**) Global fishery captures and (**b**) global aquaculture production. Aquaculture production began as fishery captures declined in the 1990s, and far outstrips fishery captures since the mid-90s. *T. philippinarum* is by far the top-ranking bivalve aquaculture species worldwide. k = 10^3 metric tons, M = 10^6 metric tons. Re-drawn from http://www.fao.org/fishery/species/search/en.

The northern quahog or hard clam *Mercenaria mercenaria* and the cockle *Cerastoderma edule* have comparatively small worldwide levels of aquaculture production (Fig. 14.6); this is partly due to their as-yet limited geographic distributions, especially for *C. edule*, restricted to the North-East Atlantic—Baltic—Barents mudflats. The cockle *C. edule* is a true mudflat species, and with or without introductions to new habitats, the margin of progression would seem to be large, since it grows at least as well as *T. philippinarum*, and usually better (higher density).

4 Clam Culture

In addition to its several common names, the Littleneck or Manila clam has had a plethora of scientific names since the original description of Linnaeus (Fischer-Piette and Métivier 1971). Originally an Indo-Pacific species, *Tapes philippinarum* was accidentally introduced from Japan into North America in 1936, along with the intended species, *Crassostrea gigas* (Quayle 1964). Its North American range now extends from Alaska to Baja California, where it is both fished and cultured (Chew 1989; Manzi and Castagna 1989). From the North American Pacific, it was introduced to both Atlantic and Mediterranean Europe in the 1970s and 1980s, specifically for aquaculture (Beninger and Lucas 1984; Shpigel and Fridman 1990; Flassch and Leborgne 1992; Pranovi et al. 2006). As was the case for *C. gigas* (see below), the aquaculture goal was amply fulfilled, and *T. philippinarum* rapidly expanded outside of the culture sites. Whereas this was perceived as a negative ecological and socio-economic development in some areas such as the Venice lagoon (Pranovi et al. 2006), it contributed to a vigorous recreational fishery in France (see Chap. 13), and a commercial fishery in Britain (Jensen et al. 2004).

The northern quahog or hard clam *Mercenaria mercenaria* is locally important as a mudflat culture species in the Eastern USA, where the dominant production site is Chesapeake Bay (https://vaseagrant.org/impacts-of-clam-aquaculture/), with other concentrated areas of production throughout New England (McHugh 2001).

Clam culture consists of seeding spat (wild or hatchery-supplied) or juveniles directly onto the mudflat. The Manila clam *Tapes philippinarum* grows best in the muddier sediments, whereas *Mercenaria mercenaria* prefers a somewhat more sandy sediment bed. Where predation is a problem, the young stages are protected by netting placed over the seeded areas (Fig. 14.8). Harvesting is usually mechanized, using a tractor fitted with a blade and a sorting mechanism to allow sub-sized animals to fall back onto the mudflat (Fig. 14.9a). Subsequent conditioning for market involves further cleaning and sizing, which is also mechanized (Fig. 14.9b).

Fig. 14.8 Installation of predator exclusion nets over seeded clam beds (Hull, Massachusetts, USA). Photo Sandy MacFarlane.

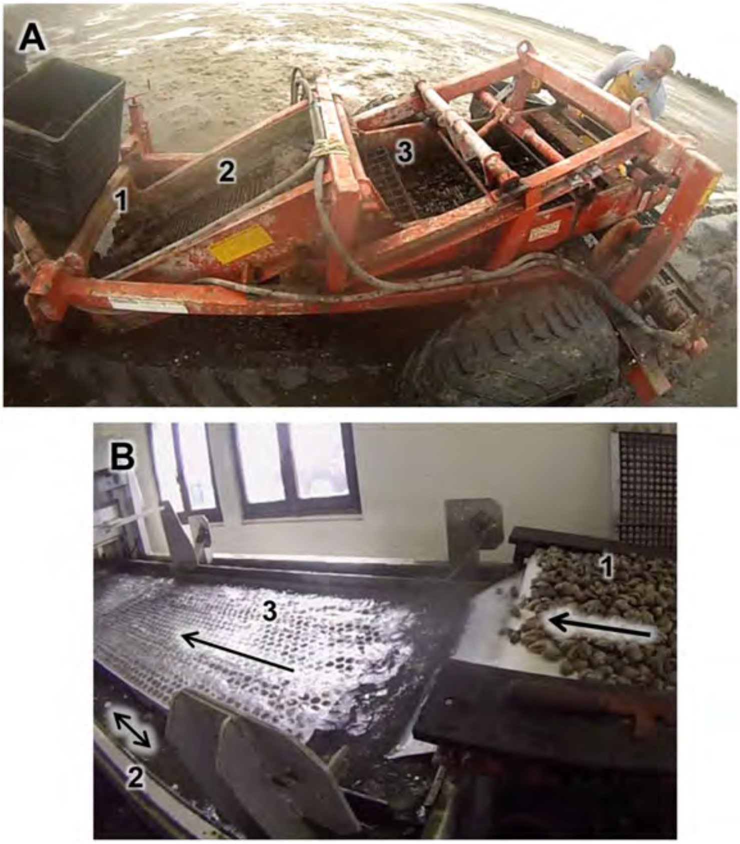

Fig. 14.9 (**a**) Manila clam (*Tapes philippinarum*) harvesting using a tractor-drawn rig which scoops the top few centimeters of mudflat (1), conveying the sediment and clams (2) to a flat, oscillating mesh (3), which allows the sediment and sub-sized clams to be returned to the mudflat. (**b**) Mechanized sorting of harvested clams. The clams are conveyed (1) to a submerged shaking mesh (2), which moves the clams forward (3). The holes in the mesh increase in size distally, so that the smaller clams fall through the mesh first; the larger clams fall through more distally, allowing them to be size-graded. Chellet-Bertheau Productions Ltd., Le Croisic, France. Photo Stewart Beattie.

5 Cockle and Arkshell Culture

Cerastoculture (cockle culture) and venericulture (clam culture) are often performed on the same mudflats, in different sectors, depending on the fine-grain content of the sediment. The cockle *Cerastoderma edule* grows best in finer sediment than that preferred by *Tapes philippinarum*, but there is considerable overlap. The cockle *C. edule* is a major parasite reservoir (see Chap. 8), and this species is also damaged by mechanical perturbation even in its adult stages (Toupoint et al. 2016); despite these drawbacks, it thrives in the aquaculture operations where it is currently grown.

Arcaculture (*Tegillarca granosa*) is an important activity in the Malaysian communities of Penang, Perak, and Selangor. The greatest development of this industry is in Perak, where about 1200 ha of mudflat are under arcaculture (http://www.fao.org/fishery/species/3503/en).

6 Mussel Culture

Two genera dominate world mussel aquaculture: *Mytilus* and *Perna*. Only the mytilids are cultured on mudflats (in addition to the subtidal), where they naturally attach to any solid substrate, large or small, including other mussel shells. The blue mussel *Mytilus edulis* is the most common species, and probably the world's largest mudflat production area is the Wadden Sea, with 58,000 metric tons and a total value of 55.5 million € in in 2005–2006 (http://www.fao.org/fishery/countrysector/naso_netherlands/en#tcN70085). This is more a type of 'ranching' than true mudflat aquaculture: the vast natural intertidal beds (Fig. 14.10) are protected from exploitation, primarily for the sake of migrating shorebirds which use them as a food resource (see also Chap. 12); this protection also allows the intertidal beds to provide a source of spat for suspended mytiliculture in the sub-tidal waters (Nehls et al. 2009).

French mussel production is much more geographically dispersed than that of the Netherlands, totalling 74,100 metric tons. French 'bouchot' mussel culture consists of simple structures such as stakes or poles inserted into the sediment, optionally with either interspersed cords for spat settlement, or wrapped with long mesh

Fig. 14.10 Protected intertidal mussel beds in the Netherlands used for seeding the exploited sublittoral zone. Photo Aad Smaal.

Fig. 14.11 Bouchot culture of *Mytilus edulis* in France. (**a**) Mud substrate (all operations performed from a flat-bottomed boat) and (**b**) mixed substrate. Photos Philippe Glize.

'sleeves' containing mussel seed (spat or juveniles—Fig. 14.11a, b). In addition to rearing the mussels to market size, this simple system actually promotes primary recruitment (the first byssal attachment) of mussel spat (Toupoint et al. 2016). Beyond the intertidal zone, mussels are commonly reared on cords suspended from floating lines or rafts.

7 Oyster Culture

As its common name implies, *Crassostrea gigas* was originally a Western Pacific species, introduced to France in 1966 for aquaculture in the wake of the *Ostrea edulis* and later *Crassostrea angulata* epizooties (*C. angulata* is so closely related to *C. gigas* that they hybridize readily in the wild). The Pacific oyster was not expected to reproduce naturally in French Atlantic waters, which were reputed to be too cold for gonad maturation; spat was to be supplied by hatcheries. The species has since established itself as an invasive pest on the French coast, and has moved northward as far as the Baltic and Shetland Islands, due to both larval drifting and introduction (including hatchery spat introduction—Meistertzheim et al. 2013; Lallias et al. 2015; Anglès d'Auriac et al. 2017; Batista et al. 2017; Shelmerdine et al. 2017). Localized coastal warming in sheltered bays has probably contributed to the spread (Dutertre et al. 2009a, b, 2010), but it is also probable that cold-resistant strains have emerged. This species now has the double status of 'desired species' (for aquaculture, as well as for coastal engineering—La Peyre et al. 2015) and 'pest species' (everywhere else) (Troost 2010; Padilla 2010; Moehler et al. 2011). It has been introduced in temperate and cold-temperate waters for aquaculture purposes around the world (Figs. 14.12 and 14.13). In comparison, the American Eastern Oyster *Crassostrea virginica* has a diminutive aquaculture production (Fig. 14.14).

Oysters grow naturally on the benthos, attaching to any solid substrate, including other oyster shells, and in the wild several species tend to form variably-massive reefs (Fig. 14.14a). Their excellent growth above the sediment has led to different forms of three-dimensional culture; on mudflats, these vary from the familiar 'oyster bags' set on 'oyster tables' (Fig. 14.15) to more recent 'hanging cages' (Fig. 14.16).

Fig. 14.12 Main producers of cultured *Crassostrea gigas*. Aquaculture of this species has been very successful in temperate and cold-temperate waters globally. Source: http://www.fao.org/fishery/culturedspecies/Crassostrea_gigas/en.

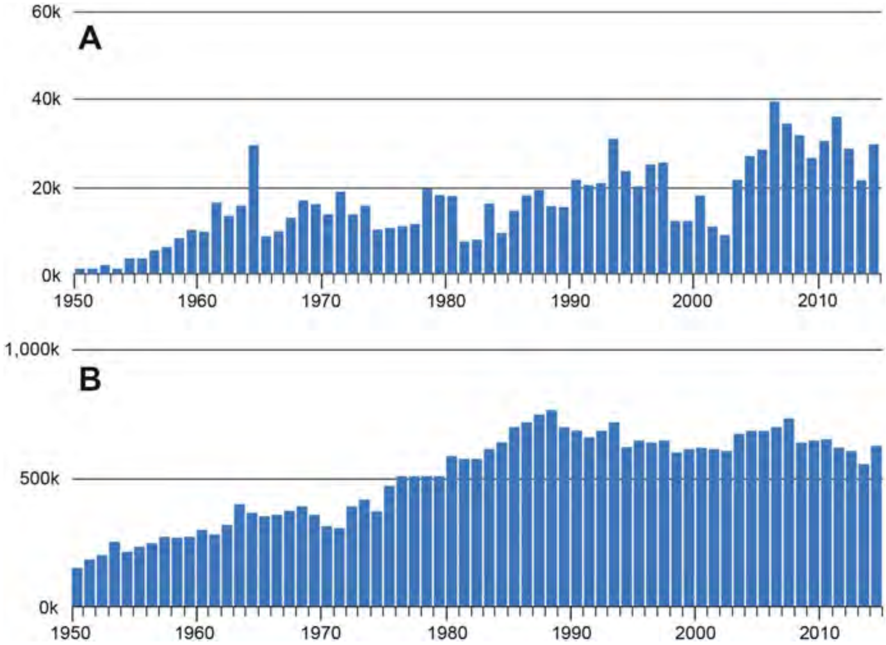

Fig. 14.13 *Crassostrea gigas* (**a**) global fishery captures and (**b**) global aquaculture production; k = 10^3 metric tons. Aquaculture production far surpasses fishery captures. Re-drawn from http://www.fao.org/fishery/culturedspecies/Crassostrea_gigas/en.

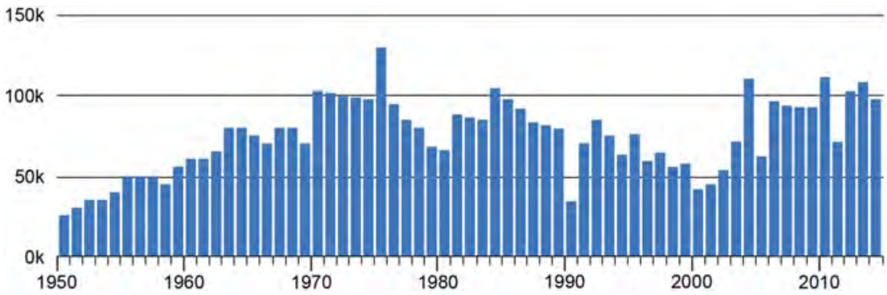

Fig. 14.14 *Crassostrea virginica* aquaculture production. Current levels are similar to those of the 1970s. Re-drawn from http://www.fao.org/fishery/species/2669/en.

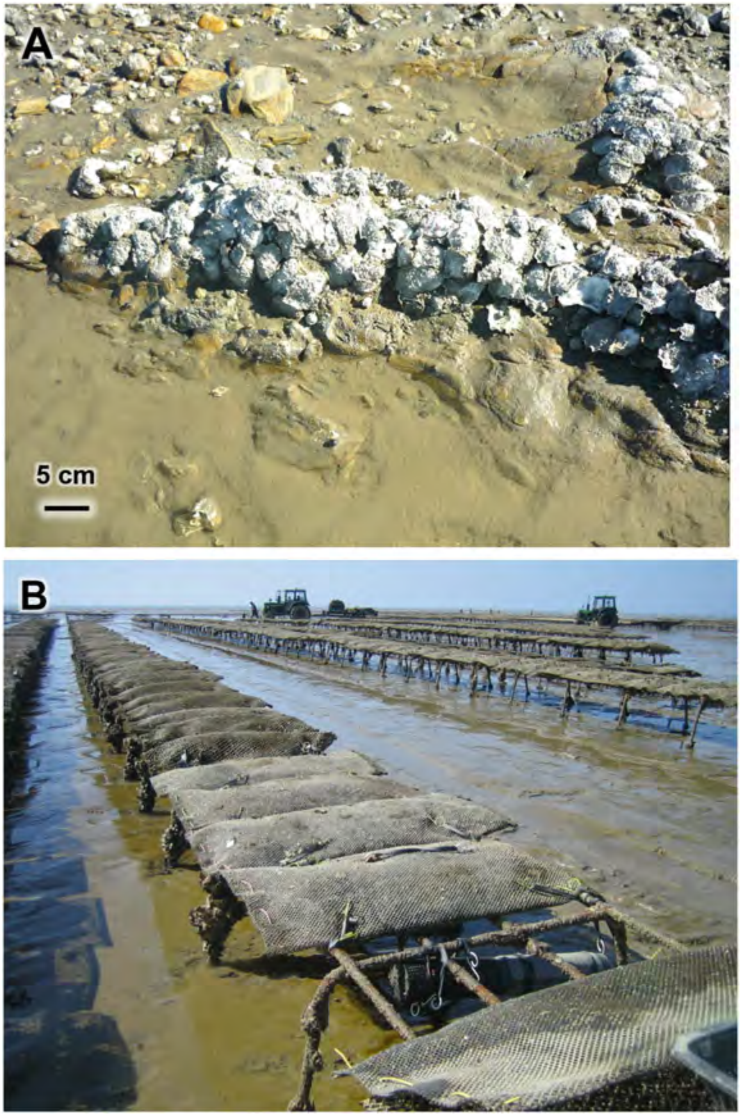

Fig. 14.15 (**a**) Small *Crassostrea gigas* reef, La Bernerie, France, photo PG Beninger. (**b**) *Crassostrea gigas* reared in oyster bags on metallic tables directly on the mudflat in France. Note the microphytobenthic biofilm on the sediment surface directly beneath the tables. Photo Philippe Glize, Syndicat Mixte pour le Développement de l'Aquaculture et de la Pêche en Pays de la Loire.

Fig. 14.16 Off-bottom mudflat cage culture of oysters in the Gulf of Mexico. Photo courtesy of NOAA.

8 Environmental Issues

Just as agriculture has profoundly modified terrestrial environments, it is to be expected that aquaculture will modify marine environments, both positively and negatively. Early documentation emphasized the fate and effects of inputs in fish aquaculture (Ritz et al. 1989; Bjoerklund et al. 1990; Hansen et al. 1990; Beveridge et al. 1991; Handy and Poxton 1993; Wu 1995); however, aquaculture inputs are not an issue in mudflat aquaculture. Additional environmental issues were subsequently addressed, including particle dynamics, bioturbation, pest/pathogen introduction, and habitat alteration. The rapidly-growing literature was brought together in a synthesis by Shumway (2011), and a 'checklist' of problems and possible solutions was supplied by Klinger and Naylor (2012).

It is of course difficult to define what constitutes a ‘positive’ or ‘negative’ environmental effect. In the strict arithmetic sense, a given activity may be considered to have a positive effect if it increases any environmental measure. In real life, however, evaluations of environmental effect invariably incorporate some conscious or unconscious anthropic bias; hypoxia or anoxia in surface sediments are not likely to be looked upon favourably, regardless of how much this is appreciated by prokaryotic anaerobes. Thus environmental outcomes which promote aerobic conditions and eukaryotic (especially metazoan) diversity are favoured, and conditions which preserve or enhance the number and diversity of charismatic vertebrates, such as migratory shorebirds (see Chap. 12), tend to be looked upon most favourably.

Most impacts of mudflat aquaculture can be considered either positive or negative, depending on both degree and on the anthropic viewpoint. Some of these will be examined in the following paragraphs.

Mudflats are subjected to frequent tidal emersion, and this attenuates several problems encountered in subtidal aquaculture, such as hypoxia/anoxia of surface sediments due to excessive biodeposition. The same constraint reduces the available periods of suspension-feeding, such that particle depletion will also be attenuated. Mudflat aquaculture thus has a built-in reducer of some environmental problems, in the form of the tidal cycle.

8.1 Turbidity and Particle Dynamics

The effects of increased filtration, respiration, biodeposition (feces and pseudofeces), and dissolved nutrient release have been explored in bivalve aquaculture operations in the past four decades (Mattson and Lindén 1983; Smaal and Prins 1993; Hatcher et al. 1994; Prins et al. 1996; Newell 2004). The concept of 'carrying capacity' emerged first in relation to the suspensivore-driven depletion of particulate food in the water column, and ultimately reflected the awareness of the constraints imposed by all of the processes generated by shellfish aquaculture (Dame and Prins 1998; McKindsey et al. 2006; Newell 2007). Although difficult to measure precisely, due to the difficulty of accurately determining phytoplankton biomass, as well as the standing crops, filtration rates, and productions of all of the attendant suspension feeders not under culture, application of the concept of 'carrying capacity', within more general management models, is considered essential to the success of bivalve aquaculture operations (Ferreira et al. 2011).

Moderate particle depletion may limit phytoplankton blooms and associated nocturnal fish kills. It has been suggested that shellfish growers receive a form of remuneration in recognition for the roles of cultured bivalves in nutrient cycling and suspended-particle regulation (Ferreira et al. 2011). Conversely, it is intuitively obvious that severe particle depletion will be accompanied by near-simultaneous high rates of biodeposition on poorly-flushed mudflats, and this must be taken into consideration when planning aquaculture operations (Rice 2008).

8.2 Eutrophication

Although shellfish aquaculture operations can be expected to increase nitrogen and phosphorus loads (Bouwman et al 2011), in a review of the impact of shellfish aquaculture with respect to eutrophication, Burkholder and Shumway (2011) stressed that only 7% of the systems examined showed severe eutrophication impact related to the aquaculture operation. These were all located in poorly-flushed, shallow lagoons. In general, bivalve aquaculture actually remediates, albeit to a small extent, the effects of terrestrial inputs which promote eutrophication (e.g. sewage, fertilizers), through the grazing of phytoplankton that would otherwise bloom, including toxin-producing species. Regular harvesting of cultured bivalves, however, is a practice with some potential for reducing the amount of eutrophic substances in coastal ecosystems (Lindhal 2011).

8.3 Biodiversity

Well-known in agricultural systems, the negative relationship between aquaculture (especially fish culture) and biodiversity was identified and explored in the early 1990s (Beveridge et al. 1994). While some of the identified drivers of biodiversity decline, as a result of fish aquaculture, are absent or not limiting in bivalve aquaculture (feed, water, waste accumulation, chemotheraputants), others are present, such as increased microorganism and parasite loads, reduction in macrofauna, alteration of population genetic structure (Arnold et al. 2004, 2009; Hargrove et al. 2015; Filgueira et al. 2015), and loss of habitat and niche space.

Conversely, biodiversity may be improved simply through the well-known positive effect of increased tridimensional complexity. For example, mudflat aquaculture infrastructure may act as refugia for the early life stages of various non-target species, including those of commercial interest (DeAlteris et al. 2004; Tallman and Forrester 2007), as well as generate an increase in the densities of grazing molluscs and juvenile fish which feed upon the fouling organisms (Spencer et al. 1996).

8.4 Habitat Disturbance

Habitat disturbance is a major driver of alterations in biological and demographic processes, spatial and temporal variation in habitat suitability, and natural selection and evolution (Banks et al. 2013). Habitat disturbance includes very real and concrete aspects such as the circulation of shellfish farmers and their tractors and rigs on the mudflat (Fig. 14.9a), as well as the installation of rearing infrastructure (e.g. racks, bouchots, antipredator netting, etc.—Figs. 14.8 and 14.11). It is well-known that mere human trampling can negatively impact sediment-dwelling organisms, including mudflat infauna (Rossi et al. 2007; Reyes-Martínez et al. 2015), so it can be expected that heavy vehicular traffic will exacerbate this impact. There is a pressing need for more research on this topic.

Whereas extensive aquaculture infrastructure has been installed on mudflats in countries such as China, with little or no resistance from the local inhabitants, a definite NIMBY (‘not in my back yard’) tendency has emerged in countries where public contestation is possible and prevalent. As Rice (2008) has observed, ‘*. . .relatively affluent coastal populations often express reservations over the loss of recreation and aesthetic values that are often articulated in the rhetoric of* *environmental protection*'; it is true that, if one sets aside the positive environmental impacts, the negative environmental impacts of aquaculture provide convenient, ostensibly objective grounds for contestation. In such situations, the 'social carrying capacity' of a given site is often attained well before the ecological carrying capacity (McKindsey et al. 2006).

9 Toward an Integrated Mudflat Management Approach

It is today considered a mark of true enlightenment when the social sciences become involved in ecosystem management (e.g. Cranford et al. 2012), and a veritable apotheosis when they then assume the dominant role. Abundant opportunities arise for devising forms and having them filled out, of writing weighty reports with attractive graphics, hiring many bureaucrats, mediators, ombudspeople, facilitators, outreach specialists, and their indispensable assistants, and of inviting politicians of all levels to engage their own bureaucracies to formulate new laws and regulations. As this process tends toward the cumbersome, it is somewhat simpler to look to other systems for examples of integrated (or at least diverse, which is often the same thing) mudflat management incorporating aquaculture. The Jiangsu mudflat, encompassing nearly 900 km of Chinese coastline, with an area of 6500 km^2 (Anonymous 1986), supports diverse economic activities, of which aquaculture occupies 37% (Fig. 14.17). Aquaculture production has steadily risen on this mudflat, surpassing the natural production of shellfish in 2007 and 2008 (Table 14.3).

In the end, the continued growth of mudflat aquaculture will depend on the area yet undeveloped, and the public resolve to allow such development will vary greatly by country. There is currently very little growth margin in densely-populated

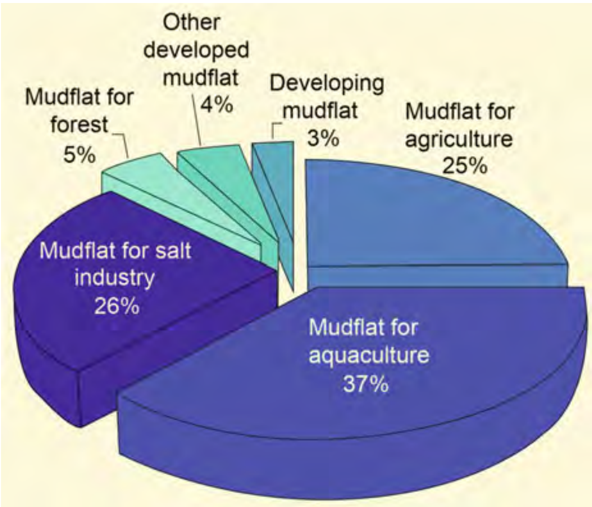

Fig. 14.17 Economic uses of the Jiangsu mudflat in mainland China [re-drawn from Wang and Wall (2010), with permission from Elsevier].

Table 14.3 Estimated natural production, aquaculture production, and aquaculture product value for mudflat-produced shellfish on the Jiangsu mudflat, mainland China

Year	Nature product ($\times 10^3$ tons)	Aquaculture product ($\times 10^3$ tons)	Aquaculture product value ($\times 10^9$ USD)	Aquaculture area (km^2)
1990	306.8	31.7	–	668.7
1995	567	83.8	–	879.4
2000	660	248.7	–	1441.8
2005	582.8	551.5	1.768	1729.5
2006	575	396.7	2.003	1454.7
2007	573.5	625.6	2.087	1481.6
2008	578.1	674.4	2.515	1600.9

Aquaculture production surpassed natural production in 2007 and 2008 [re-drawn from Wang and Wall (2010), with permission from Elsevier]

countries such as in Europe, where new permits have been generally frozen in the past decade, and private use of intertidal space for commercial activities has met with considerable opposition in many developed nations. Similarly, there is little margin for growth in the competing human and non-human uses for mudflats, and in that of the human population itself. As they have in the past, epizooties will probably decimate cultures with little or no premonition, and this must be considered an inevitable risk of the trade. Alternative species may not always be locally-available, so the issue of species introductions (frequent in previous decades, and increasingly prohibited) and subsequent invasion control (see Chap. 11) will also emerge. It is likely that worldwide mudflat aquaculture production will reach a plateau well before the human population does.

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