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OYSTER SHELLS AS VECTORS FOR EXOTIC ORGANISMS

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ABSTRACT Oyster shell may be taken from one bay and placed in another for a variety of purposes, including the restoration or enhancement of native oysters or other native species. Whereas it is generally appreciated that undesirable organisms can be transferred with live oysters, oyster shells alone can also serve as vectors for the accidental introduction of marine organisms to new locations. We here describe oyster shell plantings made for various purposes, the potential for these plantings to inadvertently transfer live organisms, and biosanitary procedures that could limit these transfers.

KEY WORDS: oyster shell, exotic organisms, *Crassostrea gigas*, *Crassostrea virginica*, *Ostrea lurida*, Olympia oyster, *Perkinsus marinus*

INTRODUCTION

Living oysters have long been moved around the world and planted in new waters to support commercial cultivation or, on occasion, to establish a wild fishery. In his landmark study, The Ecology of Invasions by Animals and Plants, Charles Elton (1958) suggested that oysters are like "a kind of sessile sheep, that are moved from pasture to pasture in the sea" and described oyster culture as "the greatest agency of all that spreads marine animals to new quarters of the world." Many oyster pests and parasites have been spread with transfers of live oysters (Ruesink et al. 2005).

Oyster shells have also been placed in coastal waters for use in oyster culture (serving as cultch, a settling surface for oyster seed) and to create or improve habitat for native oysters and other organisms. When shells are imported from other locations, there is a potential for introducing exotic organisms. A variety of organisms attach to oyster shells or live in tubes attached to them, including algae, protozoans, sponges, hydroids, anemones, serpulid worms, limpets, mussels, barnacles, tanaids, amphipods, tunicates, and others with yet other unattached worms, molluscs, crustaceans, and so on nestled in and among them (e.g., Wells 1961, Maurer & Watling 1973). Nearly any of these may be transported on freshly shucked oyster shells, or on older shells that are bathed by the tides. It is less clear what live marine organisms may be transported with shells that have been piled above the tide line for a time.

Here we examine the practice of oyster shell transfer and placement, its possible role in species introductions, and approaches to managing the risk of introductions.

Oyster Shell Planting, Including Habitat Restoration and Enhancement

Shell is used in oyster restoration in two forms: as the substrate on which seed oysters are stocked and as shell without seed used to build or rehabilitate oyster reefs. Large quantities of shell of the eastern oyster *Crassostrea virginica* have been planted in Atlantic coastal waters to restore oyster reefs since at least the 1850s in New York, the 1880s in Florida and around 1900 in North Carolina, with about 12,000 m^3/y of oyster shell planted in North Carolina between 1958 and 1994 (Street et al. 2005, Zajicek 2007, Mann & Powell 2007). Shell budgets have shown that shell removed by oyster harvesting must be replenished if the shell resource is to be maintained (Powell & Klinck 2007). Shell planting has been further encouraged by studies on the ecological functions of restored oyster reefs (e.g., Meyer et al. 1997, Meyer & Townsend 2000, Harding & Mann 2001, Peterson et al. 2003, Nelson et al. 2004), though Mann & Powell (2007) argue that widespread shell planting has not been effective at restoring reefs. With some shell planting programs limited by the availability of oyster shell, various other materials have been tested and used (Homziak et al. 1993, Haywood et al. 1995, Soniat & Burton 2005), though oyster shell remains the preferred material in most cases. In an effort to increase the supply, North and South Carolina have set up oyster shell recycling programs in which shells from backyard oyster roasts and other retail uses are deposited at shell drop-off stations, whence they are collected for use in rebuilding reefs (Street et al. 2005, SCDNR 2007a). Nevertheless, most of the oyster shell used for reef restoration in South Carolina is imported from the Gulf of Mexico (Bushek et al. 2004), and even the recycled shell may include shells from both imported and locally-grown oysters.

Starting around 2000, shells of the Pacific oyster *Crassostrea gigas* have been deployed at sites on the U.S. Pacific coast in efforts to restore the native Olympia oyster *Ostrea lurida* Carpenter 1864†. These shells have been used as substrates for stocking *O. lurida* seed oysters and for monitoring settlement and as a starter substrate for the development of native oyster beds. Though much smaller quantities of shell have been used than in Atlantic coast restoration efforts, the volume is growing (Table 1). In addition, commercial *C. gigas* growers on state oyster reserves in Willapa Bay, Washington are required to place a quantity of shell back on the reserve sites equal to 40% of the volume of live oysters harvested, or an average of about 2,000 m^3 of shell per year (Cook et al. 1998). *C. gigas* shell is also used as cultch for the seed of exotic oysters (primarily *C. gigas*, but including *C. sikamea*, *O. edulis*, and possibly other species) that

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†The taxonomy of the Olympia oyster has been in dispute since Harry (1985) proposed synonymy of *Ostrea lurida* Carpenter 1864 and *Ostrea conchaphila* Carpenter 1857. Polson et al. 2009 provide molecular evidence that the Olympia oyster refers to the nominal species, *Ostrea lurida* Carpenter 1864. In view of their genetic data, and for consistency, the original taxon, *Ostrea lurida*, is used throughout this volume to refer to the Olympia oyster, which is distributed from approximately Baja California (Mexico) to southeast Alaska.

TABLE 1.

Examples of *Crassostrea gigas* shell used in native oyster restoration projects on the U.S. Pacific Coast.

Location	Date	Volume or area	Source of shell	Purpose	Reference
Fidalgo Bay, WA	2002–06	289 bags	South Puget Sound and Lummi Bay	stocking *O. lurida* seed	Dinnel et al. 2009
Fidalgo Bay, WA	2004	15 bags	South Puget Sound	substrate	Dinnel et al. 2009
Fidalgo Bay, WA	2005	19 bags	Samish Bay	recruitment monitoring	Dinnel et al. 2009
Fidalgo Bay, WA	2006	8 m^3	Samish Bay	substrate	Dinnel et al. 2009
Fidalgo Bay, WA	2007	30 bags	South Puget Sound	recruitment monitoring	Dinnel, pers. comm.
Liberty Bay, WA	<2003	?	?	stocking *O. lurida* seed	Robinette & Dinnel 2003
Liberty Bay, WA	2005–06	≈230 m^3	?	substrate	Brumbaugh et al. 2006
Liberty Bay, WA	proposed for 2007	0.8 ha	?	substrate	WDFW 2007
Dogfish Bay, WA	proposed for 2007	0.2 ha	?	substrate	WDFW 2007
Brownsville, WA	<2003	?	?	stocking *O. lurida* seed	Robinette & Dinnel 2003
Budd Inlet, WA	<2003	?	?	stocking *O. lurida* seed	Robinette & Dinnel 2003
San Francisco Bay, CA	2001	1,000 shells	Washington state	recruitment monitoring	M. McGowan, pers. comm.
San Francisco Bay, CA	2004–05	≈3,000 kg (≈50,000 shells)	Washington state	substrate	N. Cosentino-Manning, pers. comm.
San Francisco Bay, CA	2006–07	≈40 m^3	Drakes Estero, CA	substrate	R. Abbott, pers. comm

are grown on lands owned or leased by commercial oyster farms, on small private holdings in Washington state, and on public beaches in Puget Sound where they have been planted by government agencies to support recreational harvesting (Toba 2002, P. Dinnel, pers. comm.).

Crassostrea gigas shell taken from Willapa Bay has also been planted in Grays Harbor, the next embayment northward, to provide nursery habitat for Dungeness crab *Cancer magister* as mitigation for the loss of an estimated 650,000 y1+ crabs by navigation channel dredging in 1990 (Visser et al. 2004, Armstrong et al. 1991, McGraw et al. 1988). Following an assessment of test plots in 1990–91, shell was laid at two sites in 1992, one covering 6.7 ha with 5–7 cm of shell and the other covering 2.2 ha with 10–15 cm of shell (= 5,500–8,000 m^3 of shell). Additional shell was laid each year from 1994 to 2000, totaling about 8 more ha covered with 10–25 cm of shell (= 8,000–20,000 m^3 of shell) (Feldman et al. 1997, Visser et al. 2004). Other uses have included the application of crushed-shell-and-gravel mixtures by commercial clam growers to improve habitat for native and exotic hard-shell clams (*Protothaca staminea* and *Venerupis philippinarum*, respectively) since at least 1965 (Thompson 1995) and the intertidal placement of about 45 m^3 of *C. gigas* shell from Tomales Bay, CA in San Francisco Bay to create two bird habitat islands in 2000 (S. Burke, pers. comm.). Laying 10–15 cm of *C. gigas* shell over bottom sediment has been suggested as a method of reducing the density of ghost shrimp (*Neotrypaea californiensis*), which damage oyster beds in Washington estuaries (Feldman et al. 2000).

Organisms that Could be Transported with Oyster Shell

Despite this large-scale and long-term planting of oyster shell in coastal waters, there has been little investigation of which organisms might be transported and introduced with the shell. Bushek examined material from oyster shell piles and conducted field experiments to assess the persistence of oyster tissue and the survival of the protozoan *Perkinsus marinus*, which infects oyster tissues and causes Dermo disease. In *C. virginica* shell material that had been imported into South Carolina from the Gulf Coast and dried on land for about six months before it was to be used for reef restoration, he identified *P. marinus* cells both in desiccated oyster tissues on shells (consisting of remnants of adductor muscle) and in intact oysters. He suspected, but did not confirm, that these cells were viable and transmissible (Bushek & Hudson 1997). In a subsequent experiment, shucked and fresh whole *C. virginica* oysters from Texas infected with *P. marinus* were buried 0.5 m deep in small (≈3.5 m^3) shell piles in South Carolina. Some shucked oysters still had tissue after 31 days but not at 73 days, whereas 13% of the whole oysters had tissue remaining at 115 days from which *P. marinus* was recovered. *In vitro* culture of *P. marinus* recovered from 73-day-old tissue was unsuccessful. Monitoring during the final month of the experiment showed that temperatures within the pile were cooler and less variable than ambient temperatures (Bushek et al. 2004).

Aside from microorganisms in oyster tissue, the marine organisms that are most likely to survive in oyster shell piles are high intertidal and supralittoral organisms that can tolerate extended periods out of the water wetted only by sea spray or by the dampness retained in crevices and under rocks. Common organisms in this zone include various species of lichens, littorinid and pulmonate snails, halacarid mites, chthamalid barnacles, ligiid isopods, and talitrid amphipods. Carlton (1979) reported a small Asian snail, *Cecina manchurica*, in Willapa Bay ''under masses of discarded oyster (*Crassostrea gigas*) shells [where] they are found a few inches down [in an] accumulation of damp, rich organic detritus,'' and a small, northwestern Atlantic pulmonate snail, *Myosotella myosotis*, on the surface of the same shell piles. The European green crab *Carcinus maenas* can survive at least 60 days out of water when sheltered under seaweed, and over 100 days held in bottles with gravel whose interstices were filled with seawater (Perkins 1967); in experiments, *C. maenas* resumed normal feeding after 94 days without food (Perkins et al. 1965). The eggs of some marine and brackish-water fish can also remain out of water for a significant period before hatching: diamond killifish *Adinia xenica* eggs can survive up to 24 days, California grunion *Leuresthes tenuis* eggs up to 35 days, mummichog *Fundulus heteroclitus* eggs up to 37 days, and marsh killifish *Fundulus confluentus* eggs up to 80 days (Martin 1999).

Oyster shell need not be moved great distances to serve as a vector for introducing exotic organisms. Exotic species diversity can vary significantly along a coast, so that an exotic species can occur and even be widespread and abundant in one bay for many decades without becoming established in a nearby and apparently equally suitable bay. Examples include the channeled whelk *Busycotypus canaliculatus*, native to the North Atlantic, which has been fairly widespread and sporadically common in San Francisco Bay since the 1940s, and an Asian clam, *Corbula amurensis*, which has been widespread and sometimes astonishingly abundant in San Francisco Bay since 1987, and yet neither of these species has ever been recorded from any other site on the North American Pacific Coast (Cohen & Carlton 1995, Cohen 2005). Nor is the risk limited to the introduction of a novel species; the introduction of a novel genotype of a species that is already present may also cause harm if it is more aggressively invasive or more pathogenic. For example, the oyster parasites *Perkinsus marinus* and *Haplosporidium nelsoni* (which causes MSX disease) occur in genetically distinct strains in different parts of their North American ranges, with apparently different levels of virulence (Bushek & Allen 1996, Ulrich et al. 2007).

Biosanitary Procedures

Various approaches have been used or recommended to reduce the risk of transporting and introducing undesirable organisms with oyster shell. At the Coast Oyster plant on Willapa Bay, where oysters are trucked in from Humboldt Bay, CA for shucking and processing, the Washington Department of Fish and Wildlife requires the shucked shells to be baked in a propane oven before they can be planted in Willapa Bay or other waters (B. Kauffman, pers. comm.). This requirement was initially instituted to prevent the spread of *Carcinus maenas*, which had become established in Humboldt Bay a few years earlier. In general, shell that comes from a site with a known oyster disease cannot be placed in disease-free waters in Washington (R. Rogers, pers. comm.), and shell being transferred from an area infested with the Japanese oyster drill *Ocinebrellus inornatus* must be inspected and found to be drill-free before it can be planted in an uninfested area (B. Kauffman, pers. comm.). In Oregon, placement of shell in state waters requires a permit, but there are no requirements for any inspection or treatment of the shells (M. Hunter, pers. comm.).

In California, the Department of Fish and Game required an inspection of oyster shell at Drakes Bay Oyster Company on Drakes Estero before it was transported to San Francisco Bay for use in native oyster restoration. We conducted the inspection in July 2006. The shell consisted of lower valves of *C. gigas* in a pile that covered 170 m^2 and rose 1–2 m in height. A trench about 2 m wide, 3 m long and extending down to the soil at the bottom of the pile was excavated from the bayward edge of the pile to its center. The shells in the front meter of the pile were darker colored and most had a thin, black, dry residue of adductor muscle tissue which was missing from the shells in the rest of the pile. We qualitatively sampled shells from the entire length and depth of the trench, and identified 24 species of dead marine organisms and several species of common live terrestrial arthropods (Table 2). We found these observations to be fully consistent with the owner's description of the shell pile being at least 1.5 y old and untouched by the tides in that time, and on that basis concluded that the shell would be unlikely to introduce exotic species into San Francisco Bay (Cohen & Zabin 2006).

TABLE 2.

Species collected from an oyster shell pile at Drakes Estero, CA.

Taxon	Species	Status
	Marine Organisms	
Protozoa	*Gromia oviformis*	?
Porifera	sponge	dead
Porifera	boring sponge	dead
Annelida: Polychaeta	serpulid #1	dead
Annelida: Polychaeta	serpulid #2	dead
Annelida: Polychaeta	spirorbid #1	dead
Annelida: Polychaeta	spirorbid #2	dead
Arthropoda: Crustacea: Cirripedia	*Balanus glandula*	dead
Arthropoda: Crustacea: Cirripedia	*Chthamalus dalli*	dead
Arthropoda: Crustacea: Isopoda	*Paracerceis cordata*	dead
Arthropoda: Crustacea: Amphipoda	Gammarid amphipod	dead
Arthropoda: Crustacea: Decapoda	*?Cancer* sp.	dead
Arthropoda: Crustacea: Decapoda	*Pachygrapsus crassipes*	dead
Mollusca: Gastropoda	*Collisella ?limatula*	dead
Mollusca: Bivalvia	*Hiatella arctica*	dead
Mollusca: Bivalvia	*Modiolus rectus*	dead
Mollusca: Bivalvia	*Mytilus* sp.	dead
Mollusca: Bivalvia	bivalve #1	dead
Mollusca: Bivalvia	bivalve #2	dead
Bryozoa: Ctenostomata	*Amathia* sp.	dead
Bryozoa: Cheilostomata	*Bugula* cf. *neritina*	dead
Bryozoa: Cheilostomata	*Cryptosula pallasiana*	dead
Bryozoa: Cheilostomata	*Schizoporella* cf. *unicornis*	dead
Bryozoa: Cheilostomata	*Watersipora* cf. *subtorquata*	dead
	Terrestrial Organisms	
Mollusca: Gastropoda	*Helix aspersa*	live
Arthropoda: Crustacea: Isopoda	*Armadillidium vulgare*	live
Arthropoda: Crustacea: Isopoda	*Porcellio scaber*	live
Arthropoda: Hexapoda: Insecta	insects, several species	live
Arthropoda: Hexapoda: Insecta	?Dipteran pupae	dead?
Arthropoda: Chelicerata: Arachnida	spiders, several species	live

The most widely used biosanitary procedure is air-drying oyster shells in piles on land, often a short distance above the high tide line; however, there is no consensus and limited data on the length of time that shells should be dried. The Nature Conservancy in its ''Practitioners' Guide'' to shellfish restoration (Brumbaugh et al. 2006) recommends drying shells on land for at least a month, citing Bushek et al. (2004). The Washington Department of Fish and Wildlife requires oyster shells to be kept in a pile at least 200 feet from any body of water for at least 90 days before they can be moved from one site to another, a rule that was instituted either in the 1940s (R. Rogers, pers. comm.) or sometime in the 1960s to the 1990s (B. Kauffman, pers. comm.). The rule doesn't appear to be based on any specific studies, but agency staff believe that the required 90 days is sufficient to kill *O. inornatus* and its egg cases during dry conditions, though possibly not during wet conditions (B. Kauffman, pers. comm., R. Rogers, pers. comm.). Staff of the California Department of Fish and Game would like oyster shell to be kept out of the water for 6 mo before being placed in waters within the state, though it's unclear whether the agency has authority to require this (T. Moore, pers. comm.). Whereas there are no specific studies showing that six months is either a necessary or sufficient period of drying, residues of oyster tissues observed in a 6-mo-old shell pile suggest that organisms may sometimes be able to survive at least that long (T. Moore, pers. comm.). The South Carolina Department of Natural Resources' website similarly recommends drying shell for 6 mo before planting, though it also states that research is needed to determine the appropriate minimum drying time (SCDNR 2007b).

To date, the only study relevant to the minimum time needed for shell drying is that of Bushek et al. (2004), who reported that holding oyster shells for 1–3 mo in a pile ''may reduce or even eliminate'' the potential for spreading *P. marinus*, although in the experiment described earlier they found that some *P. marinus* cells (of uncertain viability) remained after almost 4 mo. They recommended that oyster shell ''be quarantined on land for at least a month if not longer'' and that, as regards *P. marinus*, the occasional whole oysters that occur in shell piles ''represent the 'worst case scenario' and should be used to establish minimum quarantine duration.'' However, they cautioned that several factors required further investigation, including the likelihood that oyster tissue would decompose more slowly and *P. marinus* would survive longer in cooler or more humid conditions or if placed in larger piles or deeper in piles (where ambient conditions would be more thoroughly buffered). They also noted that the survival in shell piles of other oyster pathogens and of human pathogens associated with oysters has not been investigated; and neither, we would add, has the survival of other exotic and pest species that might be found in association with oysters or oyster shells.

CONCLUSIONS

It is clear that the transport and planting of fresh oyster shell, and of shell up to some unknown age, has a significant potential to transfer other organisms between sites. Measures targeting specific known oyster diseases or pests or other known, undesirable organisms—including such measures as inspections of shipments and prohibitions on transfers between infected and uninfected sites—are unlikely to be effective for the range of organisms that might be transported with shells. Baking shells in an oven, as is currently required of and practiced by an oyster processor in Willapa Bay, could be highly effective but is unlikely to be widely adopted because of the cost of equipment, labor, and fuel. What has been and is likely to remain the most common method of treatment is to dry the shells in piles on land out of reach of the tides. Taken together, observations of temperatures being cooler and less variable within oyster shell piles, observations of the persistence of oyster tissue, and the presence of microorganisms in those tissues after periods of up to six months, and evidence that some organisms of marine origin can tolerate long periods out of water in cool, humid conditions, suggest that air-drying periods of up to several months long, and perhaps longer in cool or wet periods, may be needed to effectively reduce the risk of species introductions *via* plantings of oyster shell. Thus far there has been little pertinent research, and many variables have yet to be investigated.

The rapidly growing interest in using oyster shell in coastal restoration projects on both North American coasts suggests that the quantity of shell transported and used in restoration is likely to increase. Before the transfers of oyster shells increase much further, it would be wise to conduct the research and develop the protocols needed to prevent the transfer of harmful organisms along with them.

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