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Hard Clam Mercenaria mercenaria

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HABITAT REQUIREMENTS FOR CHESAPEAKE BAY LIVING RESOURCES

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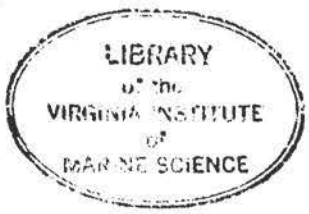

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HARD CLAM
Mercenaria mercenaria

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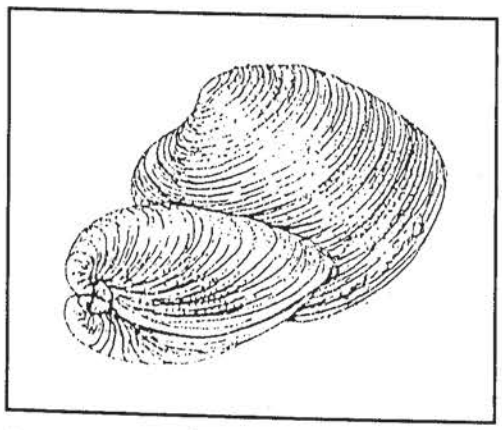

The hard clam is found along the eastern coast of North America from the Gulf of St. Lawrence to Texas. In Chesapeake Bay, the hard clam is restricted to salinities above approximately 12 ppt. An extensive survey of hard clam resources is overdue. Statements concerning long term trends in populations are not feasible.

Hard clams grow to a maximum shell length of about 120 mm. There are few documented cases of diseases in wild hard clam populations. Parasitic infestations are also slight. The life cycle of the hard clam includes a pelagic larval phase and a relatively sedentary benthic juvenile and adult phase. In Chesapeake Bay, ripe gametes can be found between May and October, and spawning commences when temperatures rise above 20-23 °C. The larvae are planktotrophic (feeding). Metamorphosis usually commences at a shell length of 200-210 mm. Predation on new recruits is very high; dense aggregations of hard clams have been found in the absence of predators. Aside from predation and fishing pressure, the natural mortality of larger clams appears very low.

Hard clams are important suspension-feeding infauna, thus they are important in grazing of primary production, transfer of carbon and nitrogen to benthic food chains, and, through excretion, rapid recycling of particulate nitrogen as ammonia. The major food source for hard clams is planktonic microalgae. In Chesapeake Bay, growth occurs in spring and fall, when optimum water temperatures coincide with abundant food.

Clams are capable of living in a variety of sediment types, but higher abundances are found in coarse-grained sediments. Hard clam stocks are susceptible to overfishing. Recruitment rates are poorly understood, as are possible reestablishment periods if areas are depleted through commercial harvesting, and factors influencing larval settlement rates.

Hard clam mariculture is well established and could easily be expanded into sites within the Bay.

Given the ability of clams to bioaccumulate toxic substances, adequate monitoring should be maintained. The sublethal effects of toxic material readily found in the lower James River should be examined.

INTRODUCTION

The hard clam is an important member of the suspension-feeding, benthic infuana of the lower Chesapeake Bay, where it exists in salinities above 12 ppt. Commercially exploitable stocks exist in several areas of the Virginia portion of the Bay and have become increasingly important in recent years as watermen look for alternatives to the declining oyster fishery. In the face of continuing threats from bayside development and stock exploitation, comprehensive surveys of the hard clam in the Bay are long overdue; much data is over 20 years old. The purpose

of this document is to provide the reader with a broad summary of aspects of the natural history of the hard clam in the Chesapeake Bay so that potential impacts of shoreline development and other activities affecting the aquatic environment can be assessed in terms of environmental requirements of the hard clam in the Bay.

BACKGROUND

Geographic Range

The hard clam also is commonly known as the quahog, little-neck clam, or cherrystone clam. It is distributed along the Atlantic coast of North America from the Gulf of St. Lawrence to Florida and along the Gulf of Mexico coast from Florida through Texas.[1,58] The hard clam has been introduced to California and Europe.[7,70] It is restricted to salinities above approximately 12 ppt, and is most abundant in polyhaline estuarine waters. Its depth range extends from the intertidal zone to greater than 18 m.[58]

In Chesapeake Bay, *M. mercenaria* is the only common hard clam. Baywide surveys of clam populations are few; however, the hard clam's potential estuarine distribution is mainly determined by salinity, and it is not abundant below 18 ppt. In the Maryland portion of the Bay, hard clam populations are restricted to Pocomoke and Tangier Sounds,[81] although deposits of old shells are found in the lower Patuxent. The bulk of the Chesapeake hard clam distribution is located in the Virginia portion of the Bay, particularly in subestuary river systems with salinities exceeding about 12 ppt and depths greater than than 5 m.[6,34] Surveys have found hard clams to be widely distributed in the Chesapeake Bay, but commercially exploitable abundances are limited to an area of about 12,000 acres. These high density distributions are concentrated in the lower York and James rivers.[68] Limited commercially exploitable abundances are also found in the lower Rappahannock River, Mobjack Bay, and along the western side of the Eastern Shore.[65,67,68]

Distribution and Population Status

The potential habitat of hard clams in Chesapeake Bay includes areas where the bottom salinity exceeds 12 ppt, which corresponds to approximately 17 ppt during summer; larval metamorphosis is impeded below 17 ppt.[40,87] Adult hard clams can tolerate salinities to about 12 ppt, but do not grow. Hard clams are capable of small local migrations, pushing out of the sediment and moving before the current. An 18 mm clam can be moved by a 25 cm s^{-1} current. The abundance of clams within a habitat is simply the number of larvae which settle minus those that die after settlement. The surviving clams may then be redistributed by local currents. Comprehensive studies of larval densities and settlement rates have not been made for Chesapeake Bay sites. Limited data have been reported for areas outside the Bay. Carriker[32] reported a density of 572 larvae L^{-1} in Little Egg Harbor, New Jersey, whereas seed densities as high as 270,000 m^{-2} have been recorded in Maine.[47]

Because regular surveys of hard clam resources in Chesapeake Bay have not been made, long term trends in populations cannot be determined. Results of several local surveys of hard clam populations in the Virginia portion of the Chesapeake Bay are summarized in Table 1. Unexploited populations of hard clams in the Chesapeake Bay usually are composed of significantly more large individuals than new recruits or juveniles.[68,72] In the bulk of the populations sampled by Haven *et al.*,[68] greater than 70% of the clams were more than 6 cm in shell length, with an estimated age of 4-8 years. In another survey, the highest density of clams smaller than 3.6 cm in shell height was found to be only 0.44 clams m^{-2}, compared with a density of 3.22 clams m^{-2} for clams larger than 5.8 cm at the same site.[72] In the James River, where densities of adults were among the highest in the Bay, the estimated annual recruitment was less than one clam m^{-2}.[65,68] Low recruitment may be the result of high larval mortality, low settlement rates, heavy predation on post-settlement clams or some combination of these factors. The hard clam is a long-lived species, and individuals have been aged at more than 30 years.[64,91]

Morphology

Hard clams grow to a maximum shell length of about 120 mm. The valves of the hard clam are thick, inequilateral, ovate-trigonal, and joined at the hinge by a thick brown external ligament. The shell is sculptured with fine concentric ridges which separate and coarsen at the umbones, while at mid-shell the ridges diminish to a characteristic smooth spot. The valves do not gape. A distinguishing external feature is the heart-shaped lunule, located anteriorly to the prominent external ligament. The lunule is typically 3/4 as wide as long. Internally, the ventral margin of the shell is crenulate. The hinge architecture is strong, and the anterior and posterior adductor muscle scars and the pallial sinus are prominent.

The outer shell of hard clams ranges in color from yellowish to white, although specimens collected from reduced sediments may be darkly colored. The interior of the shell is usually white, tinged with dark purple patches. The shells were valued by American Indians as wampum.[58] Growth patterns within the shell may reflect the environmental history of the individual.[90] The basic anatomy of hard clams conforms to that of venerid bivalves. The shell-secreting mantle lines the valves and encloses the viscera, and is fused posterio-ventrally into the short inhalant (incurrent) and exhalant (excurrent) siphons. The siphons are muscular and retractable, ending in tactile and chemosensitive tentacles. The strong, hatchet-shaped foot extends anterio-ventrally and is used to burrow into the substrate.[10]

LIFE HISTORY

Spawning and Reproduction

The life cycle of the hard clam is typical of other venerid bivalves, and includes a pelagic larval phase and a relatively sedentary benthic juvenile and adult phase.[32,87]

The hard clam is a protandrous, consecutive hermaphrodite and is dioecious after changing sex (i.e., the clams begin adult life as males, often become females with greater maturity, and require individuals of both sexes for reproduction). Sexual maturity is mainly a function of size.[17,84,85,104] Clams develop functional male gonads at 6-7 mm in shell length in the first or second year of life. Oocytes are sometimes present at this time. After this juvenile male phase definitive sexes are established at a size of about 30 mm shell length.[7,54,83,84]

Spawning cycles are affected mainly by temperature and food availability, and thus vary according to latitude. From north to south, the development and duration of ripe gametes tends to begin earlier and extend longer.[54] Spawning often occurs in pulses and may continue for months,[44] but usually there are one or more distinct spawning peaks; a second spawning peak often occurs from North Carolina south.[2,54] When ripe gametes have been produced, spawning is stimulated by a temperature increase over some threshold. In Chesapeake Bay, ripe gametes can be found between May and October,[37] and spawning usually commences when temperatures rise above 20-23 °C [6] (personal communication: M. Castagna, Virginia Institute of Marine Studies).

Fecundity in hard clams is high. Females can release 16-24 million eggs per spawn,[44] although laboratory studies often have recorded lower values of 1-3 million eggs.[78] With repeated spawns individuals may release up to 60 million eggs over a season. The viability of eggs and subsequent survival of larvae are positively related to egg size, not clam size,[7,79,88] but the amount of spawn released increases with increasing clam size.[17] Eggs are 60-85 µm in diameter when released, and covered with a gelatinous membrane which expands in contact with water, further extending the diameter to 163-179 µm.[32] In culture experiments, however, eggs will often pass through a 35 µm mesh; they are retained on a 25 µm mesh. Fertilization occurs in the water column.

Larval Development

The larvae of hard clams are planktotrophic (feeding), and development of the larval forms follows the usual blastula, gastrula, trochophore, straight-hinged (90-140 µm), umboned (140-220 µm), and pediveliger (170-230 µm) stages of bivalve molluscs.[37,87] Rate of development is highly dependent on temperature, salinity, availability of high quality food, and turbidity; under optimum conditions the larval stage can be completed in as little as a week.[86] On the other hand, the larval stage can be maintained for at least 24 days if conditions are inadequate or suitable substrate is lacking.[86]

Mature pediveliger larvae have a well-developed, ciliated foot and byssus gland in addition to a functioning velum.[32] The pediveligers alternate swimming with crawling on the bottom using the foot. This behavior facilitates testing the substrate for suitable settling sites. Pediveligers can distinguish between different sediment types, although the selective mechanisms involved are unclear.[76] Distribution of settling larvae within the estuary probably reflects a combination of active site selection and passive deposition.[24,129] During settlement, the pediveliger anchors itself to the substrate with a byssal thread, thereby terminating the period of planktonic life.[32] It is unclear whether the velum is absorbed or cast off at settlement. Degeneration of the velum may precede settlement. The ciliated foot of the pediveliger also serves as a swimming organ. The settled clam is now termed a "byssal plantigrade", which slowly metamorphoses into a juvenile clam. Metamorphosis is gradual, and entails development of the digestive viscera and gills, fusion of the mantle edges, and development of the siphons. Metamorphosis usually commences at a shell length of 200-210 µm.[87]

Young byssal plantigrades initially lie at or just under the sediment surface, but can move about on the foot, while the byssal threads can alternately be detached and reformed. The exhalent siphon ususally is developed at metamorphosis, but the inhalent siphon usually does not appear until a shell length of approximately 1.5 mm. As the siphons develop and elongate, the byssal plantigrade burrows progressively deeper in the substrate. The siphons initially maintain contact with the overlying water, but after the formation of siphonal tentacles, which aid in the exclusion of sediment from the inhalent stream, the clam may be completely buried. At a shell length of about 7-9 mm, the byssal gland is lost and the byssal plantigrade becomes a juvenile plantigrade. The juvenile clam can move about by means of the shortened, hatchet-shaped foot.[32]

Growth

The hard clam exhibits seasonal, latitudinal, and size-related variations in growth.[8,55] In warm-temperate areas such as Chesapeake Bay, the most significant growth occurs in spring and fall, when optimum water temperatures coincide with abundant food (see **Habitat Requirements**). Growth decreases in summer, and ceases in winter (at water temperatures less than 9°C). Seasonal growth increments increase along the north-south latitudinal gradient; thus clams grow to market size earlier in areas with longer growing seasons.[8] Growth rate also tends to decrease with age.[55,102] As growth ceases either with old age or adverse conditions, clams become thicker ("blunt") rather than increase in shell length.

Hard clams exhibit wide geographical variation in growth rates. Growth model estimates indicate that 2.5 years are needed for clams to reach 3.8-5 cm, and 4.5 years to exceed 6 cm on Hampton Flats, Virginia. In contrast, in the lower salinity areas of the York River, 4-5 and 8 years are required to reach the respective size classes. Chowder clams at the same locations were estimated to be 8-20 years old.[65,67,82]

ECOLOGICAL ROLE

Feeding

Hard clams are important members of the suspension-feeding infauna. Therefore, they are important in benthic-pelagic coupling, grazing of primary production, transfer of carbon and nitrogen to benthic food chains, and through excretion, rapid recycling of particulate nitrogen as ammonia. The major food source for hard clams is planktonic microalgae.

Normally, clams lie buried in the substrate with only the siphons communicating with the sediment surface. Specialized gill cilia draw a respiratory and feeding current down the inhalent siphon, through the gills, and out the exhalent siphon. Food particles brought in by the inhalent stream are filtered out by cilia, trapped in mucus strings, and transported to the labial palps, where the material is sorted by size. Organic and inorganic particles in the size range of about 5-15 µm are imbedded in mucus strings and ingested. Material rejected from the sorting cilia on the gills or labial palps is concentrated near the base of the inhalent siphon and periodically ejected by forceful adduction (closing) of the valves. The rejected material is called pseudofeces. The sensory tentacles on the inhalent siphon can reduce the aperture to limit inhalation of sediment.

Filtration rates of hard clams are related to food concentration. Feeding efficiency increases with increasing particle density up to a maximum, and then decreases at higher particle concentrations.[119] Optimum algal density for hard clam filtration is 2×10^5 cells ml^{-1}.[118] Clams have been observed to assimilate 71.2-77.3% of the ingested food.[119] Maximum filtration rates were found to be dependent on the species of algae.[125] Feeding rates also increased directly with temperature and current velocity.[125]

Predation

Predation on newly recruited hard clams is very high, and is known to have eliminated entire sets of both natural and planted stock.[9,33,67,93,97] Dense aggregrations of hard clams were found in the absence of predators.[92] In Chesapeake Bay, the blue crab appears to be the primary predator on juvenile hard clams,[5,33,56,66] although oyster drills, whelks, and mud crabs also are significant predators.[6,56] Flatworms can cause problems where clams are cultured out of their natural substrate. The cownose ray is common in Chesapeake Bay[14] and is capable of feeding on the larger sizes of hard clams.[6,35] Other important predators include horseshoe crabs, herring gulls, and finfish (tautog, puffer, black drum, and flounder).[54] Many predator species prevalent in other areas (e.g., sea stars) are prevented from affecting Chesapeake Bay hard clam populations by low salinity.

The size of clams interacts with crab size and substrate characteristics to form refuges from predation.[56,57,92,127] Crabs feed by crushing small clams and chipping away the edges of larger clams,[114] but clams larger than about 6 cm shell length are immune from most crab predators.[54] Boring gastropods (e.g., oyster drill snails) also probably prey more extensively on thinner-shelled, younger individuals. Intense predation on small individuals may explain their poor representation in the size-frequency distributions of populations. Densities of clams often are higher in seagrass beds than in surrounding sand flats,[100] and gravel or shell aggregate has been shown to reduce crab predation.[35,57,92]

Aside from predation and fishing pressure, the natural mortality of larger clams appears to be very low.[6] Clams maintained in predator exclusion cages in South Carolina had an estimated mortality of 1.43%.[49] There are few documented cases of diseases in wild hard clam populations,[113] although the hard clams in Canada reportedly were decimated by disease.[116] Parasitic infestations also are slight.[54]

HABITAT REQUIREMENTS

Temperature

Temperature affects hard clam reproduction, and growth of larvae and adults. Gametogenesis begins when water temperature reaches about 10°C,[54] and temperature is one of the main stimuli for spawning. Critical spawning temperatures vary geographically due to acclimation of populations to local conditions.[78] In Chesapeake Bay, spawning usually begins in May when water temperatures rise above 23°C.[75,77]

Younger life stages generally have narrower temperature tolerances for survival than adults. Eggs remain viable from 7.2-12.5°C to over 32.5°C,[43,77,89] but embryos and trochophores at temperatures above 30°C experienced increased mortality with increased exposure time.[77] Larvae survived temperatures between 12.5 and 30-33°C,[32,87] the best survival rate was between 22.5-25.0°C at 22.5 ppt salinity.[43] Adult hard clams can survive temperatures between -6 and 45.2°C.[69,129] Activity of adults is curtailed below 1°C and above 34°C,[63,123] and is optimal between 21 and 31°C.[119]

Larval growth and survival are functions of both temperature and salinity.[73,89] Growth of larvae ceases at <12.5°C,[87]

mainly because the larvae cannot assimilate ingested food.[43] The optimum temperature for growth at most salinities (≤ 27.0 ppt) is 25-30°C, and the optimum temperature range for larval growth from fertilization to ten days at 21.5-30 ppt salinity is 22.5-26.6°C. Temperature also affects the developmental rate of larvae: the time between fertilization and settling has been found to be 20 days at 18°C (16-24 days) and 7.5 days at 30°C (7-9 days). Growth of adults occurs between 8°C and about 31°C,[3,12] with an optimum temperature of 20°C.[3,102,109] The latter values are below those quoted earlier[109] and probably reflect inhibition of bacterial activity at the lower temperatures.

Salinity

Salinity significantly affects both growth and survival of hard clams. Larval forms are more sensitive to adverse salinity levels than adults. The salinity range for normal egg development is 20-35 ppt,[40,43] with an optimum of about 27 ppt.[87] High mortality occurs at less than 12-17 ppt.[34,36,87] The upper and lower salinity limits for normal larval development are 15-35 ppt, indicating that larvae can exist in lower salinity regimes more successfully than eggs.[87] Metamorphosis, however, is inhibited at less than 17 ppt.[40,87] Optimum salinity for growth and survival to settlement is 26-27 ppt.[34,40,43,87]

The synergistic effect of salinity and temperature on larval growth and survival results in a limiting of the ranges of temperature tolerance with a reduction in salinity, especially at high temperatures and low salinities.[43] Thus higher mortalities and slower growth of larvae are expected at less than 17.5 ppt. The minimum salinity tolerance for adults is approximately 12 ppt, whereas clams can exist in waters of oceanic salinity[114] and above. For example, hard clams have been recorded in Laguna Madre, Texas, at salinities up to 48 ppt! The ability of hard clams to adduct the valves tightly reduces the negative effects of short term environmental fluctuations. Reproduction is inhibited at less than 15 ppt.[34] Thus salinity is a major factor in hard clam distribution patterns. In Chesapeake Bay, clams are not abundant at less than 20 ppt[6] (personal communication: M. Castagna, Virginia Institute of Marine Science).

Dissolved oxygen

Dissolved oxygen (DO) usually is not a limiting factor for hard clams in Chesapeake Bay. Anoxic events usually are concentrated in lower salinity, upper Bay areas outside the salinity tolerance range for metamorphosis, or in deeper regions where clams are scarce. Additionally, clams of all life stages exhibit a marked tolerance to low DO. The minimum DO requirement for normal development is about 0.5 mgL^{-1}, although growth rates are reduced greatly below 4.2 mgL^{-1}.[98] Short term stress does not affect later development.[98] Adult hard clams can maintain oxygen consumption down to DO levels of 5.0 mgL^{-1}, after which oxygen consumption declines and, presumably, anaerobic metabolism becomes responsible for a greater proportion of total metabolic activity.[62,63] Dissolved oxygen concentrations of less than 5.0 mgL^{-1} clearly represent stress to hard clams. Activity can be maintained even at DO concentrations less than 1.0 mgL^{-1}.[109]

Turbidity

Heavy sediment loads have negative effects on growth and survival, although clams usually can tolerate ambient concentrations of suspended materials. Eggs suffered increasingly abnormal development with increasing silt concentration from 0.75-3 gL^{-1}; at the higher concentration, there was no normal development.[41] Larvae were not able to survive or grow in concentrations of 0.25 gL^{-1} chalk or 0.50 gL^{-1} of fuller's earth, although eggs could withstand higher concentrations.[41,45] Growth of larvae was inhibited in silt concentrations above 0.75 gL^{-1}, however, survival was high even at 4 gL^{-1}.[41,45]

High concentrations of small particles tended to clog the larval alimentary tract.[45] Juvenile and adult clams (14 and 32 mm shell length) decreased the ingestion rate of algae with increasing sediment load (up to 0.044 gL^{-1}), and lost 18% of ingested algae by increased production of pseudofeces.[18] The rate of filtration also was depressed by additions of silt.[105] Growth of hard clams was inhibited at 0.044 gL^{-1}, but not at 0.025 gL^{-1}.[19] Most of these detrimental concentrations are higher than those encountered in nature, except during dredging or very heavy runoff events.

pH

Hard clams are tolerant of most pH levels commonly encountered in their habitats. Embryos developed at pH values of 7.00-8.75, whereas larvae survived in the pH range of 6.25-8.75.[26,27] Growth occurred between pH 6.75-8.50, with an optimum between pH 7.50 and 8.50.[26,27]

Structural habitat

Substrate characteristics are important for hard clam growth, distribution, and abundance. Larvae prefer to settle in sand over mud substrates,but particle size was not deemed an important factor.[76] Clams are capable of living in a variety of sediment types. Field surveys often have found higher abundances of hard clams in sandy rather than muddy sediments; however, this distribution varies by location.[3,4,126] A heterogeneous substrate mixture of sand or mud with gravel or shell often shows high abundances of clams.[101,117] This fact appears to relate to the larger material offering a spatial refuge from predation.[9] Higher growth rates also have been observed in sand substrate.[38,60,90,102]

SPECIAL PROBLEMS

Contaminants

The toxic action of a number of organic and inorganic compounds on hard clams has been investigated. The ability to culture hard clams has allowed for the evaluation of many compounds on the larval stages. Embryos and larvae are much more susceptible to toxicants than are adults. The adults often can withstand large body burdens of toxic materials, and can concentrate these substances far above ambient concentrations. Additionally, the depuration of toxic compounds is often slow. This consideration is of obvious concern because hard clam populations, especially in the James River, often are exposed to toxicants. One important aspect of pollution biology, sublethal effects (e.g., reduction of reproductive output), is poorly understood. The following section on toxicants refers to values of LC_{50} and EC_{50}, defined as follows:

LC_{50} = concentration of a toxicant that causes death of 50% of the test organisms;

EC_{50} = concentration of a toxicant that affects a specific response (e.g., growth) in 50% of the test organisms.

Organic compounds

Concentrations of petroleum products in the low mgL^{-1} range are toxic to embryonic and larval clams (Table 2). These concentrations were measured in the field following a spill, as well as tested experimentally in an oil-spill weathering simulator.[25] Growth studies with EC_{50} end points indicated that petroleum products decreased growth rates when compared to controls.[25] This sublethal effect is important because increased mortality of clams usually is associated with longer planktonic existence. The hard clam is very sensitive to waste motor oil, which makes up a significant portion of petroleum pollution.[25]

Hydrocarbon depuration is slow. Adult hard clams depurated only about 30% of accumulated hydrocarbons in 120 days (41.9-29.3 mg kg^{-1} wet weight).[16] Clams with initial benzo(a)pyrene contamination levels of 16.0 µg kg^{-1} reduced body burdens to 8.2 µg kg^{-1} after seven weeks and had a residual of 1.1 µg kg^{-1} after 60 weeks.[111] Oiled sediments reduce the depth to which clams bury while increasing burial time.[99]

Polynuclear aromatic hydrocarbons (PAH) were found to accumulate in hard clams much faster than they were depurated, giving bioaccumulation factors in the 10^3-10^4 range[13] (Table 3); however, oysters were found to have even higher bioconcentration factors because they had significantly lower depuration rates than hard clams.[13]

In contrast to the relative tolerance levels of temperature and salinity on the early life stages of hard clams, the toxicity of the insecticides, herbicides, bacteriocides, and fungicides tested usually were greater for larvae than for eggs[42,45] (Table 4). The relative LC_{50} concentrations of the compounds vary, but generally are in the mgL^{-1} range.[42,45] Some compounds (sevin, endothal, 2,4-D salt, phenol, and sulmet) accelerated larval growth over controls; the reasons were unclear, but antibiotic properties or chelation of toxicants were suspected. Except for allyl alcohol, the organic solvents tested were not toxic.[45] Hard clams concentrate pesticides, but do not store polychlorinated hydrocarbon pesticides as well as other species (Table 5). Accumulation of a variety of pesticides was slower and depuration was faster in hard clams than in soft shell clams.[22,23] The biotic concentration factor (BCF) is a function of contaminant concentration. At a DDT concentration of 1.25 gL^{-1}, the maximum mean BCF in hard clams after 18 days was 1.8×10^3, whereas the depuration time was slightly over three months.[39] Butler[21] reported tissue accumulations of 6 µg g^{-1} after one week at a DDT concentration of 1 µg gL^{-1} (BCF = 6×10^3). At higher concentrations, DDT decreased in foot tissue after six months while the concentration in the viscera did not decrease measurably.[39] Fortunately, DDT use now is banned in the United States.

Tributyltin oxide (TBTO) was found to be highly toxic to hard clam eggs and larvae, with LC_{50} values in the parts per trillion (ngL^{-1}) range for eggs and embryos, and the μgL^{-1} range for larvae and juveniles (Table 6).[106] A TBTO concentration of 0.77 ngL^{-1} depressed growth rates, although the resulting larvae were normal.[106]

Kepone contamination of the James River estuary was recognized in 1975, and the substance was found to be present throughout the food chain. Hard clams had comparatively low body burdens of the insecticide, and no directly toxic effects were discovered.[73]

The sublethal effects of chlorinated hydrocarbon contamination include depressed glucogenesis and enhanced glucose degradation. These conditions indicate stress in the organism.[52] Other enzyme pathways may be affected.[52]

Hard clam embryos and larvae have been found to have relatively low tolerances to surfactants[71] (Table 7). Forty-eight hour LC_{50} values ranged between 0.0085-5.83 mgL^{-1}; actual field concentrations of surfactants in the St. Mary's River, Maryland, were reported at 0.06 mgL^{-1}.[71] Again, clam larvae were more tolerant than oyster larvae. In contrast, sodium nitrilotriacetic acid (NTA) was non-toxic to adult oysters;[51] 168-hour LC_{50} values were more than 10 mgL^{-1}. Hard clams were the least sensitive species examined.

Inorganic compounds

Juvenile and adult clams were relatively unaffected by high concentrations of ammonia and nitrite (Table 8); nitrate and orthophosphate had no deleterious effects[53]. The lethal values for these compounds are higher than normally encountered. In contrast, chlorine was highly toxic to hard clam larvae, with EC_{50} values near the μgL^{-1} level.[107,110]

Heavy metals were toxic to eggs and larvae of hard clams in the μgL^{-1} to mgL^{-1} range (Table 8).[28,29,30,31] Metals are known to be concentrated in hard clams at several orders of magnitude greater than in the surrounding environment. Accumulation and depuration rates are dependent on such physical factors as temperature and salinity which affect metabolic rates.[103] In hard clams taken from Southampton, England, metal accumulation was related inversely to salinity, but little correlation was found between sediment metal and tissue metal concentrations.[108] Generally, depuration rates of heavy metals from hard clams are slow. Levels of cadmium, chromium, nickel, lead, zinc, and copper either remained the same or increased after transplantation from a polluted area in Great South Bay, New York.[11] Accumulation rates, body burdens, and depuration rates of heavy metals in hard clams are low relative to oysters and soft clams.[103] Oxygen consumption rates increased with increasing silver concentrations.[120]

Heavy metal toxicity varies with life stage and types of metal. Early life stages are more sensitive to mercury and silver than to cadmium, possibly due to a lower accumulation rate for cadmium, but the order of toxicity to these metals reverses in older animals, perhaps due to tolerance to mercury and silver.[30] The relative toxicity of metals to hard clams was found to be copper > cadmium > chromium > zinc,[112] whereas metal toxicity to hard clam larvae was determined to be mercury > copper > silver > zinc > nickel (nickel was relatively nontoxic).[31] Body burdens of cadmium, copper, and zinc were determined in hard clams from the James and York Rivers and several sites in Chesapeake Bay.[80] The concentrations of these metals within samples (zinc 5.0-112 $\mu g\ g^{-1}$, copper 1.0-16.5 $\mu g\ g^{-1}$, and cadmium < 0.8 $\mu g\ g^{-1}$) generally were comparable with other studies; however, the metal content of clams in the James River was higher than in the York River or in the mainstem Bay, suggesting heavy metal contamination in the James.[80]

RECOMMENDATIONS

Research

The ability to manage a resource requires a firm knowledge of the status of the resource. The abundance and distribution patterns of hard clams in Chesapeake Bay are poorly described and are based upon information from studies of nearly 20 years ago. A more extensive contemporary survey of hard clam resources is urgently needed. Further, the early life history of hard clams in the Bay has not been investigated. Larval settlement rates and annual recruitment, and the factors which influence these processes are poorly understood. Basic research is needed to address these problems.

Harvesting

Hard clam stocks are susceptible to overfishing. Recruitment rates are poorly understood, as are possible reestablishment periods if areas are depleted of clam populations by commercial harvesting. Hydraulic dredges are efficient harvesting tools capable of eliminating the bulk of the clams in an area. Patent tongs probably are much less efficient and allow some clams to persist under present fishing stress. Control of the method of harvest is a prudent measure to control fishing mortality.

Mariculture

Hard clam mariculture is well established and easily could be expanded into sites within Chesapeake Bay, although site specific salinity might influence clam growth and hence, the economic viability of mariculture endeavors.

Toxics

Given the ability of hard clams to bioaccumulate toxic substances, an adequate system to monitor body burdens of toxicants should be maintained. The sublethal effects on clams of toxic substances readily found in the lower James River should be examined.

CONCLUSION

The hard clam clearly is an important member of the suspension feeding infauna and contributes significantly to grazing of single-celled plankton, to coupling of benthic and pelagic food chains, and to nutrient recycling in Chesapeake Bay. The hard clam also supports a significant commercial industry. Information gaps in hard clam distribution and abundance need to be filled. The deleterious effects of anoxia, turbidity, and toxic organic and inorganic compounds on hard clams need to be monitored carefully. The hard clam is a suitable candidate species for mariculture and is unusually free of natural diseases and parasites.

ACKNOWLEDGMENTS

This work was synthesized mainly from the species profiles written by Stanley and Dewitt,[115] Stanley,[114] and Eversole[54]. The annotated bibliographies collected by McHugh *et al.*[94] and McHugh and Sumner[95] were also very helpful. The draft manuscript was improved by critical review by M. Castagna, J. Kraeuter, A.G. Eversole and an anonymous reviewer. Their efforts and contributions are appreciated.

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Table 1. Literature reports of hard clam densities in the Virginia portion of the Chesapeake Bay.

Site	Density clams m^{-2}	Reference	Site	Density clams m^{-2}	Reference
Hampton Bar, James River	8.7-11.1	68	Allens Island, York River	3.9	68
Poquoson Flats	2.4	68	Gaines Point, York River	6.8	68
Lower James River	0.7-4.7	72	Mobjack Bay	1.3-2.1	68

Table 2. Toxicity of petroleum products to hard clams.[25] All LC_{50} and EC_{50} values are in mgL^{-1}.

	Embryos LC_{50}				Larvae EC_{50}	
	48 h	96 h	144 h	240 h	144 h	240 h
Kuwait crude	12	25	13.1	2.0	15.7	4.2
Southern Louisiana crude	5.7	6.0	5.3	2.1	3.2	1.1
Bunker C	1.0	3.2	1.8	1.6	1.9	1.0
No. 2 fuel oil	0.43	1.3	1.3	0.53	0.63	0.57
Florida Jay crude	0.23	0.25	0.11	0.55	0.29	0.22
Used motor oil	0.04	0.10				

Table 3. Concentration of polynuclear aromatic hydrocarbons (PAH) by hard clams.[13] Uptake rate: 28-day accumulation in mg $kg^{-1}d^{-1}$; Clearance: 28-day clearance rate in mg $kg^{-1}d^{-1}$; BCF: bioconcentration factor.

Compound	Uptake rate	Clearance rate	BCF
Benzo(a)anthrene	2824	0.172	16516
Benzo(a)fluorene	994	0.167	5943
Benzo(b)fluorene	1190	0.162	7332
Benzo(a)pyrene	361	0.087	4143
Benzo(e)pyrene	2366	0.148	15980
Benzo(ghi)fluoranthene	3384	0.145	23306
Benzofluoranthene	1857	0.180	10331
Chrysene	1190	0.162	7335
Fluoranthene	1477	0.213	6934
Methylphenanthrene	187	0.115	1628
Methylpyrene	2002	0.148	13571
Perylene	1133	0.161	7059
Phenanthrene	224	0.114	4072
Pyrene	1587	0.194	8172
Total PAH	556	0.137	4072

Table 4. Toxicity of pesticides to hard clam eggs and larvae.[42,45]

Compound	Eggs: 48 h LC_{50} mgL^{-1}	Larvae: 12 day LC_{50} mgL^{-1}
Insecticides		
aldrin	>10	0.41
co-ral	9.12	5.21
dicapthon	3.34	5.74
di-syston	5.28	1.39
guthion	0.86	0.86
lindane	>10	>10
N-3514	<1	<1
sevin	3.82	2.50
toxaphene	1.12	<0.25
Herbicides		
diuron	2.53	>5
endothal	51.02	12.50
fenuron	>10	>5
monuron	>5	>5
neburon	<2.4	<2.4
Nematocide		
Nemagon	10	0.78
Solvents		
acetone	>100	>100
allyl alcohol	1.03	<0.25
orthodichlorobenzene	>100	>100
trichlorobenzene	>10	>10
Bacteriocides, Algicides, Fungicides, etc.		
chloramphenicol	74.29	50
Delrad		0.072
Dowicide A	>10	0.75
Dowicide G	<0.25	<0.25
griseofulvin	<0.25	<1
PVP-Iodine	17.10	34.94
Nabam	<0.50	1.75
nitrofurazone	>100	>100
phenol	52.63	55.00
Omazene	0.081	0.378
Phygon	0.014	1.75
Roccal	0.19	0.14
Sulmet, tinted	>100	>100
Sulmet, untinted	>1000	>1000
TCC	0.032	0.037

Table 5. Accumulation and depuration of pesticides by hard clams.

Compound	Life stage	Dose μgL^{-1}	Accumulation mg kg^{-1} tissue	Depuration mg kg^{-1} tissue	Reference
DDT	Adult	1	3-9	3.5 (0 d) 0.88 (10 d) 0.161 (20 d)	20
		1 (7 d) 0.0125 (18 d)	6 10.0±5.8	0.5 (15 d)	21 73
Kepone	Adults		0.09[a]	1	06
Methyoxychlor	Adults	4	1.3 (gills) 0.075 (mantle)		39

[a]mean residue

Table 6. Toxicity of tributyltin oxide (TBTO) to hard clam embryos and larvae.[106]

Life Stage	Duration hours	LC_{50} μgL^{-1}
Embryo	24	>1.31
	48	1.13 (0.72-1.31)
Larvae	24	>4.21
	48	1.65
	96	0.015

Table 7. Toxicity of surfactants and syndets to eggs and larvae of hard clams.[71] All values in mgL^{-1} unless otherwise specified.

Compound	LC_{50}	EC_{50}
Anionic		
Alkyl Aryl sulfates	1.55 (0.55-3.00)	
AAS-1		5.83
AAS-2		0.98
AAS-3		1.03
Alkyl sulfate	1.22 (0.73-1.46)	
AS-1		0.47
Cationic	0.34 (0.01-1.00)	
C-1		1.27
C-2		0.85 μgL^{-1}
Nonionic	2.66 (1.00-5.00)	
N1		0.77
N2		1.75

Table 8. Toxicity of inorganic compounds and heavy metals to various life stages of hard clams.

Compound	Life Stage	Test	Concentration, uptake rate, or percent growth	Reference
ammonia	Juv. & adults	96 h LC_{50}	110-172 mgL^{-1}	53
nitrite	Juv. & adults	96 h LC_{50}	81-85 mgL^{-1}	53
chlorine	Larvae	48 h EC_{50}	6 gL^{-1}	107
		48 h EC_{50}	<6 gL^{-1}	110
		48 h LC_{50}	1 gL^{-1}	107
Ag	Embryo	48 h LC_{50}	0.021 mgL^{-1}	28
		48 h LC_{100}	0.045 mgL^{-1}	28
	Larvae	10 d LC_5	0.0186 mgL^{-1}	31
		10 d LC_{50}	0.0324 mgL^{-1}	30,31
		10 d LC_{95}	0.0462 mgL^{-1}	31
		Growth @ LC_{95}	66.2%	31
	Adult	96 h Dose	a	30
Cu	Larvae	10 d LC_5	0.0049 mgL^{-1}	31
		10 d LC_{50}	0.0164 mgL^{-1}	30,31
		10 d LC_{95}	0.0280 mgL^{-1}	31
		Growth @ LC_{50}	51.7%	31
	Adult	accumulation @0.5 mgL^{-1}	0.06 g $kg^{-1}d^{-1}$	103
		84 d depletion	50 mg $kg^{-1}d^{-1}$	103
Fe	Adult	84 d depletion	none observed	103
Hg	Embryo	48 h LC_{50}	0.166 mgL^{-1}	28
		48 h LC_{100}	0.0075 mgL^{-1}	28
	Larvae	10 d LC_5	0.004 mgL^{-1}	28
		10 d LC_{50}	0.0147 mgL^{-1}	30,31
		10 d LC_{50}	0.0147 mgL^{-1}	31
		10 d LC_{95}	0.0254 mgL^{-1}	31
		Growth @ LC_{50}	68.7%	31
	Adult	84 d Depletion	120 mg $kg^{-1}d^{-1}$	103
Mn	Adult	84 d Depletion	95 mg $kg^{-1}d^{-1}$	103
Ni	Embryo	48 h LC_{50}	0.31 mgL^{-1}	28
		48 h LC_{100}	0.60 mgL^{-1}	28
Pb	Embryo	LC_{100}	1.2 mgL^{-1}	28
	Adult	accumulation @0.2 mgL^{-1}	0.63 g $kg^{-1}d^{-1}$	103
Zn	Embryo	LC_{50}	0.166 mgL^{-1}	28
		LC_{100}	0.25 mgL^{-1}	28
	Larvae	10 d LC_5	0.050 mgL^{-1}	31
		10 d LC_{50}	0.1954 mgL^{-1}	31
		10 d LC_{95}	0.3410 mgL^{-1}	31
		Growth @ LC_{50}	61.6%	31

[a]0.100 mg kg^{-1} accumulation in gills increased oxygen consumption.