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HABITAT REQUIREMENTS FOR CHESAPEAKE BAY LIVING RESOURCES

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SOFT SHELL CLAM
Mya arenaria

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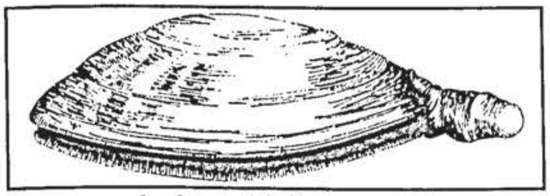

Large populations of soft shell clams persist only in relatively shallow, sandy, mesohaline portions of the Chesapeake Bay. These areas are mostly in Maryland, but also occur in the Rappahannock River, Virginia. In some other portions of the Bay, especially polyhaline portions, low populations of soft shell clams persist subtidally. Restricted populations persist intertidally.

Soft shell clams grow rapidly in the Chesapeake Bay, reaching commercial size in two years or less. They reproduce twice per year, in spring and fall, but probably only fall spawnings are important in maintaining population levels. Major recruitment events do not occur in most years, despite heavy annual sets. Soft shell clams are important food for many predators. Major predators on juveniles include blue crabs, mud crabs, flatworms, mummichogs, and spot. Major predators on adults include blue crabs, eels, and cownose rays. Some other species that may depend heavily on soft shell clams include ducks, geese, swans, muskrats, and raccoons.

Diseases may play an important role in regulating adult populations of soft shell clams; hydrocarbon pollution is linked to increased frequency of disease. Oil pollution does the most widespread and persistent damage to soft shell clams through toxicity, aside from its role in inducing disease. Heavy metals, pesticides, and similar pollutants can be extremely toxic, but the harmful effects to clams do not last if the pollution abates. The main concern with the latter toxicants is bioaccumulation by soft shell clams, with the potential for passing toxic contaminants on to predators or to humans.

Siltation caused by storm events, dredging operations, or erosion, can smother clam populations. Eutrophication, enhanced by nutrient inputs from sewage or agriculture, is not known to have affected soft shell clam populations.

INTRODUCTION

Population levels of harvestable soft shell clams have declined since exploitation began in 1953, the first year of major harvesting of Maryland soft shell clam stocks. Harvests climbed to 3,700,000 kg in 1964 and remained stable until 1971. Harvests in Virginia began in 1955, reached a peak of 180,000 kg in 1966, but ceased in 1968. Tropical storm Agnes in 1972 was responsible for poor harvests in Maryland in the early 1970's,[154] but stocks had apparently collapsed in Virginia prior to the storm. In 1973 harvests in Maryland were only 300,000 kg, but rebounded to 1,400,000 kg in 1988. There has been no significant harvest of soft shell clams in Virginia since 1968.

Soft shell clams are major components of the filter feeding benthic infauna of the mesohaline portion of the Bay, consuming microscopic algae which they filter from water drawn into their incurrent siphons. There is evidence that soft shell clams are very important in removing particles from the water, even as small juveniles. A density of 3000 juveniles averaging 2.5 mm long in an area of 1 m^2 can filter one 1 m^3 of water per day, while 1500 juveniles 5 mm long in the same area can filter 2.5 m^3 per day.

Filtering capability increases exponentially with shell length.

The abundance of soft shell clams in the Bay underscores their importance as members of the benthic infauna, yet their variability in abundance (with resulting impact on the commercial fishery) suggests a role as indicator species of temporal and spatial change in the Bay environment. Below is a brief introduction to the biology of the soft shell clam, followed by a discussion of the species' habitat requirements.

BACKGROUND

Geographical Range

The soft shell clam also is known as the steamer clam or the mannose. It is found in marine and estuarine waters, intertidally and subtidally to depths of nearly 200 m along the Atlantic coast of North America from northern Labrador to Florida, with maximum abundances from Maine to Virginia.[95,165] It also is found throughout Europe from northern Norway to the Black Sea[60,95] and has been successfully introduced to the west coast of North America from southern Alaska to southern California.[54]

Identification Aids

The soft shell clam rarely exceeds 11 cm in shell length in Chesapeake Bay,[4] and is elongate and oval in outline. The shells gape at both ends when closed, and in life the foot and the siphons protrude from either end. The fused siphons, or "neck", are covered with a leathery integument. The shell is relatively brittle (hence the name "soft shell clam"), and in life is at least partially covered with a thin grey or tan parchment-like periostracum, whereas dead shells quickly become bleached chalk-white. Inside the left-hand shell there is a spoon-like chondrophore attached to the hinge.

Distribution, Population Status, and Trends

The distribution of soft shell clams in Chesapeake Bay is restricted by several variables, particularly salinity, sediment type, anoxia, and predation. Low salinity limits the upstream distribution in most of the major tributaries: Hog Island in the James River; Tappahannock in the Rappahannock River; Mathias Point in the Potomac River, and the Patapsco River in the mainstem Bay. Sediment type does not affect survival directly, but predators virtually eradicate soft shell clams of all sizes in soft mud, so only sandy areas contain significant amounts of clams.[135] Soft sediments predominate in deeper water; water depth therefore correlates imperfectly with soft shell clam distribution.

Seasonal anoxia is normally restricted to deep waters,[89,164] which do not support soft shell clam populations, but periodic "seiching" events, or tilting of the density gradient, can temporarily inundate shallower areas with anoxic water.[170] There is no physiological reason why soft shell clams cannot survive in deep water, and individuals have been collected in Chesapeake Bay from as deep as 15 m.[127] But populations persist mainly in shallow areas of the Bay, particulary in areas of less than 5 m. The reported persistence in shallow water may be a sampling artifact, since most sampling for adults has been done in less than 5 m;[69,135] however, the distribution of soft shell clams is consistent with the general distribution of coarse sediments.

Although soft shell clams survive well in high salinity, indirect factors limit sustained high population levels to mesohaline portions of Chesapeake Bay. High salinity allows many predators to be active for more of the year. In shallow and mesohaline portions of the Bay, clams have more time to grow to a size that limits predation. Predation pressure therefore places an effective upper salinity limit on soft shell clam distribution.

In Chesapeake Bay optimal areas for soft shell clams are found on the Eastern Shore from Pocomoke Sound to Eastern Bay, and on the western side from the Rappahannock River to the Severn River in Maryland. The northward "deflection" of this distribution on the Eastern Shore may be due to higher salinities on that side of the Bay. Ideal conditions may exist in small areas in other portions of the Bay also, and low population densities exist throughout most of the Bay. We have chosen the relatively arbitrary level of one adult soft shell clam per m^2 as a definition of high abundance; throughout most of Chesapeake Bay abundance is much lower. Juvenile abundance may greatly exceed 1 m^{-2} temporarily in almost any part of the Bay. Potential distribution, averaged for a variety of conditions, is shown in the Map Appendix.

Multi-year trends in salinity, temperature and anoxia may temporarily expand or contract this range. Within-year variations allow juveniles to settle in outlying areas, but these populations rarely survive more than a year.[33,147] Juveniles often set in high abundances in areas with low adult abundance, but are virtually eradicated within months.[69,76,77,176] In addition, episodic events such as high summer temperatures, high predator abundances, or low salinity can eradicate adults in small areas[126] or large areas.[31,71] These areas can be recolonized quickly when conditions once again become favorable,[65] but since bivalve larvae tend to be retained within their native subestuaries,[105,149] severely affected subestuaries would probably take longer to recover.

Although soft shell clams reproduce twice in most years, juveniles that recruit in spring rarely survive because of predation pressure, regardless of the magnitude of recruitment.[77,176] Only clams spawned in the fall, and therefore able to grow in cold water when predators are inactive, survive to a size large enough to avoid most predators.[171] Even then major recruitment events may occur only every ten to fifteen years.[70] Based upon our observations, severe temperature shifts can eliminate large numbers of recent recruits to intertidal populations in a short period. There is evidence that large amounts of drifting macroalgae can inhibit settlement of soft shell clams.[125] Attached macrophytes (e.g., submerged aquatic vegetation) on the other hand, enhance settlement by slowing currents.[81] Recruitment events within different subestuaries are likely to be independent because bivalve larvae tend to be retained within subestuaries.[105,149]

In lower regions of Chesapeake Bay soft shell clam populations are less abundant, except in intertidal areas. The intertidal region may have greater than 20 adults m^{-2} while subtidal areas have virtually no adults[102] (our observations). This distribution probably is due to the coarse intertidal sediments and the limited time that clams are exposed to predators.[111,145] If spawning success is affected by the density of adults,[128] these intertidal populations are probably vital to maintaining recruitment of juveniles subtidally.

Population levels of harvestable soft shell clams have declined since exploitation began in 1953,[173,174] but the reasons are unclear. In 1950 the hydraulic escalator harvester was invented, and in 1953 major harvesting of Maryland soft shell clam stocks began. Prior to 1953 the maximum harvest had been 730 kg (meat) in 1949,[108] but harvests rapidly climbed to a maximum of 3,700,000 kg in 1964, and remained nearly stable until 1971.[173,174] Harvests in Virginia began in 1955 and were much more irregular, reaching a peak of 180,000 kg in 1966, but ceasing in 1968. Extreme mortality of adult soft shell clams in parts of Chesapeake Bay caused by tropical storm Agnes in 1972 was responsible for poor harvests in Maryland in the early 1970's,[154] but stocks had apparently collapsed in Virginia prior to the storm. In 1973 harvests in Maryland were only 300,000 kg, but rebounded to 1,400,000 kg in 1988. There has been no significant harvest of soft shell clams in Virginia since 1968. All evidence in Virginia (which has limited soft clam populations in most areas) suggests that large settlements of juveniles can be produced by small populations of adults.[32,33,34,35,69] Soft shell clams also appear to be resistant to domestic sewage and low levels of industrial pollution.[3,78,99] So little is known about fisheries dynamics that we cannot say that there are not natural population trends on the scale of decades.[144] Since virtually every exploited fishery stock for which data has been kept has shown a significant overall decline,[144] the possibility exists that declines in soft shell clam populations in Chesapeake Bay may be partially due to exploitation.

LIFE HISTORY

Spawning and Fecundity

Soft shell clams usually spawn twice per year in Chesapeake Bay; once in mid- to late autumn, and once in late spring. The actual times depend on the temperature of the water, because the clams can spawn only in water between 10-20°C, and spawn most efficiently at 12-15°C.[102,133] Optimal temperatures occur only for a few weeks each year, and if the length of time that these conditions exist is too short, the clams may not spawn at all. This situation happens most often in spring.[102,150,151]

During spawning both eggs and sperm are released externally. It has been found that the success rate of external fertilization for other benthic invertebrates decreases sharply with both sperm dilution and sperm age. Both of these factors increased with the distance between spawning adults, so higher densities of adults led to higher fertilization success.[128] Assuming that this principle holds true for soft shell clams, it means that areas with high adult population density contribute disproportionately to the production of larvae.

Sexes are separate in soft shell clams, with equal numbers of males and females,[17,102] although Appeldoorn[5] found a slight but significant bias towards females in Long Island Sound. Fecundity, or the number of eggs produced per female, increases exponentially with female size.[17] A clam with a shell 3 cm long can produce only about 1,300 eggs per spawning episode, whereas a 5 cm clam can produce 9,300 eggs, and a 10 cm clam, 85,100 eggs. Larger clams, therefore, are disproportionately important in maintaining population levels.

Eggs and Larval Development

Egg size varies from about 42 to 73 µm in diameter.[17,101] An egg develops into a trochophore larva within a day, and becomes a veliger larva in several more days. The veliger metamorphoses into a juvenile clam at about 200-300 µm in shell length[101,119] in about one to three weeks, depending partly on temperature.[102,163] During their larval phase bivalve larvae are planktonic, swimming just strongly enough to maintain themselves at some level of the water column. When the larvae are ready to metamorphose they alternately swim near the bottom and crawl on the bottom for several hours before settling.[101] Gregarious settlement has been reported.[73] The newly settled clams, or spat, usually attach themselves to any available substrate with byssal threads secreted by the foot.[101]

Juveniles, Growth, and Adults

Although adult soft shell clams are completely sedentary, small juveniles up to about 15 mm long can be very active. If hard substrate, such as shell, worm tubes, eelgrass, or coarse sand is available, they will attach themselves to it with byssal threads. These threads are often released while the young clam crawls about with its foot. It also may burrow temporarily during this period of its development.[101,157] Eventually the clam burrows permanently, and unless disturbed, spends the rest of its life in place. Clams can be disturbed and redistributed by strong tidal or storm events. The depth of the burrow increases with age, so that the top of the shell can be 2 cm below the surface when shell length is only 1 cm, 4 cm deep at a size of 2 cm, and 12 cm deep at 4 cm.[187]

Growth of soft shell clams in Chesapeake Bay is relatively rapid. Under average conditions, they can reach the marketable size of 5 cm (shell length) in 1.5-2 years.[64,107] Growth rate depends on many factors, including salinity and temperature, food abundance, sediment type, intertidal level, and pollution. Both high salinity and warm water, especially in spring, favor growth.[4,110,162] Food abundance - measured both by actual abundance and by competition with other filter-feeders - affects growth.[162]

Fine sediments favor growth, whereas sand and gravel decrease growth rates.[123] (This does not mean that mud is better soft shell clam habitat, however, as explained below in the **Habitat Requirements** section.) Intertidal clams grow more slowly both because they have less time to feed, and because the sediment tends to be coarser.[82] Some types of pollution have been shown to decrease clam growth rates, as explained under **Special Problems** below. Growth is best in summer and poorest in late winter,[121] and most growth is completed within the first five years of life. Growth decreases exponentially with age, but clams 28 years old have been found.[18,103] There is no evidence that genetic differences between populations or subpopulations affect growth rate.[159]

ECOLOGICAL ROLE

Role as Filter Feeder

Soft shell clams feed on microscopic algae which they filter from water drawn into their incurrent siphon. They consume small flagellated cells and diatoms in the 5-50 μm range,[43,110,153] and can selectively reject non-food particles and toxic dinoflagellates such as *Protogonyaulax tamarensis*.[43,152] Rejected particles are incorporated into pseudofeces, and thus are removed from the water column. Free-living bacteria are too small to be filtered,[184] but bacteria associated with detritus may be assimilated.[92] The presence of soft shell clams affects the settlement of many species of infauna, enhancing some and inhibiting others. Although rarely, some invertebrate larvae are drawn into the siphons,[51] the mechanisms of interactions between soft shell clams and infaunal settlement are not known. Differential filtration may be a contributing factor.[75]

Studies of soft shell clams outside of Chesapeake Bay suggested that the clams were very important in removing particles from the water, even as small juveniles. In San Francisco Bay, it was calculated that a density of 3000 juveniles averaging 2.5 mm long in an area of one m^2 could filter one m^3 of water per day, while 1500 juveniles 5 mm long in the same area could filter 2.5 m^3 per day. The filtering capability of adults was not calculated, but it increased exponentially with shell length.[124] These densities are high for Chesapeake Bay,[102] but even much lower densities may be significant. In waters off western Sweden, it was estimated that infaunal bivalves, including high numbers of soft shell clams, consumed nine times as much of the small plankton as did zooplankton grazers.[100] Filtering by benthic filter feeders is especially important in controlling microalgal biomass associated with eutrophication in shallow, well-mixed bodies of water, such as Chesapeake Bay.

When compared to other common Chesapeake Bay filter feeders, soft shell clams equal or exceed eastern oysters in weight-specific filtering rates, but filtering rates are lower than those of jackknife or razor clams. Ribbed mussels can filter bacteria from the water, whereas soft shell clams cannot.[88,153]

Role of Empty Shells

Despite its fragility, the shell of the soft shell clam is relatively resistant to dissolution, and its light weight makes it less likely to be buried than many shells.[42] Thus, the shell is particularly suitable as substrate for many fouling organisms, especially in areas that lack other shell or rock. Most of these fouling species are small, but two bivalve species make extensive use, directly or indirectly, of soft shell clam shells. The jingle shell requires a smooth, hard surface (such as soft shell clam shells) as a substrate, and the ark clam settles onto hydroids that grow on the shells.[41]

Predators

Predation on soft shell clams at all stages is very intense. Under most conditions 90% to over 99% of fertilized eggs and planktonic larvae are destroyed in the water column.[166,185] Jellyfish (hydromedusae and scyphozoans) and comb jellies are considered major predators of molluscan larvae.[129,139] Sea nettles, although abundant for part of the year, normally are not present when soft shell clam larvae are abundant.[179] Other potential predators on mollusk larvae include copepods, larval and juvenile fish, and filter-feeding fish such as anchovies and menhaden.[27,129,139,146] As the larvae metamorphose and settle, they fall prey to benthic planktivores such as barnacles, sea anemones, and annelid worms.[15,160,186] Mortality of newly-settled juveniles is about 90% within the first several days.[138]

It is thought that overall predation is the most important source of mortality for all juvenile and adult age classes. Benthic planktivores in high abundance can prevent settlement locally.[186] Predators can eradicate soft shell clams from an area, whether newly-settled juveniles,[50,69,80,138] or older juveniles.[76,77,119,176] Predation can keep populations from surviving in muddy substrates, where it is easier to dig down to the clam.[97] Although larger clams are less vulnerable to predation, a high abundance of predators can destroy a local clam population.[126]

Soft shell clams provide an important, direct link between phytoplankton and predators of all sizes. The relative importance of a predator on juvenile or adult clams depends both upon the proportion of its diet that is made up by soft shell clams and its overall abundance. For most predators one or both of these factors is not known, so their importance can only be estimated. Table 1 lists major and minor predators on juveniles soft shell clams, and Table 2 lists major and minor predators on adult clams. "Major" predators are defined here as animals that are abundant throughout most of the soft shell clam range in Chesapeake Bay and use soft shell clams as a significant portion of their diet. "Minor" predators are those that are not abundant, are restricted to a small proportion of the Bay, or for which soft shell clams are only a minor portion of the diet. "Juveniles" are here defined as clams with shell lengths of under 2 cm.

Mummichogs are limited to very shallow water,[74] but the other major predators are found in all water depths that sustain large soft shell clam distributions. Their importance as clam predators relative to each other is not known. Submerged aquatic vegetation reduces predation on infaunal bivalves.[130] Polychaete worms certainly have the capability of preying on juvenile clams;[53,96] Hidu and Newell[73] reviewed evidence suggesting that some polychaete worms are major predators.

Of the minor predators, horseshoe crabs, snapping shrimp, and oyster drills are abundant mainly in polyhaline areas. Mud snails are abundant in Chesapeake Bay, but less so in sandy areas, and apparently eat only extremely small bivalves.[80] Ducks and geese affect only shallow areas, but are active in winter, when most other predators are inactive.[61,83]

Adult soft shell clams, if they can be excavated, are vulnerable to predators because their shells are fragile and do not close tightly. The method of predation by eels is unknown, but crabs can excavate to 20 cm or more (personal communication: R. Lipcius, Virginia Institute of Marine Science), and rays can, by means not well understood, excavate large pits to reach adult clams (personal communication: R. Blaylock, Virginia Institute of Marine Science). Of the minor predators, all but the black drum are limited to polyhaline portions of the Chesapeake Bay.

Many species of predators, especially fish, eat mainly siphon tips of soft shell clams.[74,180] These injuries usually are not lethal to clams, but reduce the fitness of individuals, so the effects at the population level are approximately equal to the effects of removing an equal biomass of entire individuals.

Some populations of certain other species may depend heavily on soft shell clams, even though they are not numerically important predators. These predators include ducks and geese, especially overwintering populations,[61,83] and muskrats and raccoons (personal communication: J. Carlton, Oregon Institute of Marine Biology).[167]

There are four ways soft shell clams can escape most predation pressure. The first is to grow larger, because larger clams are buried deeper, and deeper clams are harder for predators to excavate.[11,76,176,187] The second is to live in coarser sediments (e.g., sand rather than mud) where predators have more difficulty excavating.[97] It follows, therefore, that even though clams grow faster in soft mud,[122] large populations cannot persist in mud in Chesapeake Bay.[135] The third partial refuge is low temperature. Clams can survive and grow at low temperatures,[12,66] when their predators are inactive. Consequently, they grow to a larger, less vulnerable size before their predators become active.[171] The fourth partial refuge is intertidal areas, an exception to the general distribution of soft clams. Intertidal areas are limited in extent in most parts of Chesapeake Bay, but soft shell clams are well-adapted to intertidal existence.[2] Intertidal areas provide a relative refuge from most predators, because there is less time for predation;[111,145] areas that do not support significant subtidal populations can sometimes support intertidal populations of adults.[69,102] Some predators, such as mummichogs, ducks, geese, whistling swans, and raccoons, are well-adapted to this zone, however, so the intertidal area is only a partial refuge. Recreational clam harvesting also occurs mainly in the intertidal region.

Low density is also thought to be a partial refuge from predation, because predators tend to seek out patches of high density prey.[97] The value of this tactic to the soft shell clam, however, probably is offset by the lower success rate of fertilization among low-density clam populations, as hypothesized above under **Life History**.

HABITAT REQUIREMENTS

Water Quality

Salinity

According to Matthiesen,[110] adults cannot survive below 4 ppt salinity for more than a few days, and do not grow below 8 ppt, but Chanley[25] reported survival after acclimatization at 2.5 ppt. Probably the lower summer salinity limit is 8 ppt. Larval salinity tolerance varies, depending upon the salinity to which the adults are acclimated,[163] but Chanley and Andrews[26] give 5 ppt as a lower limit. There is no upper salinity limit, but the prevalence of predators in water of high salinity restricts large populations of soft shell clams in the Bay to mesohaline areas. Adults can survive salinities as low as 0 ppt for about two days,[110] but longer periods cause mass mortalities.[70] Juveniles are more susceptible to low salinity than adults, and warm temperature decreases tolerance to low salinity.

Temperature

Soft shell clams can survive temperatures as low as -12 °C for long periods of time[12], so normally there is no lower temperature limit in Chesapeake Bay. Sudden and extreme temperature shifts may affect intertidal populations of juveniles, however, although Kennedy and Mihursky[87] reported that juveniles are more tolerant of temperature extremes. A sudden decrease in air temperature from 20°C to below 0°C in a few hours was followed by massive mortalities of intertidal juveniles within a day in the York River (our observations). Only juveniles recruited the previous autumn were affected. Because such temperature shifts occur mainly in the winter, they represent a major source of mortality for clams during a time when most predators are inactive. Only intertidal populations are likely to be affected, however.

Optimum temperatures for feeding are about 16-20 °C, but feeding can take place at as low as 1.5°C,[66] a temperature much lower than the minimum required for activity by most soft shell clam predators. The upper limit for soft shell clams is about 34°C,[66] a temperature rarely encountered in Chesapeake Bay. Temperature extremes do limit spawning, however, since spawning is restricted to temperatures between 10-20°C at the most.[102] Optimal spawning probably is restricted to an even narrower temperature range.[133] These temperatures are required for a period of at least several weeks for gamete maturation and successful spawning. In some years, especially in spring, temperatures rise or fall too quickly for successful spawning.[102,151] Larvae evidently can grow at a wide range of temperatures, and growth rate is independent of temperature within certain limits.[102]

pH

Seawater is naturally buffered in the salinity ranges occupied by soft shell clams, so extreme pH is unlikely to occur. Consequently there has been little study of the effects on soft shell clams of pH variations. Physiological processes in soft shell clams occur without significant inhibition over a relatively wide range of pH.[161]

Dissolved Oxygen and Depth

Although soft shell clams can survive near-anoxic conditions for as long as seven days,[112] anoxia has been known to cause mass mortalities of soft shell clams in western Sweden.[143] Seasonal anoxia in some deep portions of the Chesapeake Bay[89,164] has miminal impact on soft shell clam populations because they are restricted largely to shallow areas. If anoxia is extensive, however, and prolonged "seiching" events, or tilting of the density gradient, occur, anoxic deep water can inundate shallow areas[170] and cause mortalities of benthic organisms. It is not known to what extent anoxia in the Bay is enhanced by domestic sewage and agricultural runoff, but these inputs correlate with anoxia and mass soft shell clam mortalities in waters off western Sweden.[143] If eutrophication and the extent of seasonal anoxia in the Chesapeake Bay are increasing, as some have suggested, the frequency and duration of shallow water anoxic events also will increase. A "catastrophic" anoxic event in 1984 apparently threatened shellfish beds in Maryland.[148]

Structural Habitat

Adult soft shell clams removed from their burrows eventually die unless they can reburrow;[72] they can reburrow quickly only into very soft sediments.[136] Although they grow most quickly in soft sediments,[123] they are also most vulnerable to predators there.[97] Large populations in Chesapeake Bay persist only in muddy sand and sandy mud.[135] Soft shell clams can survive in very coarse sediments (our observations).[122]

SPECIAL PROBLEMS

Contaminants

Metals

Industrial pollution typically contains a suite of metal ions in various concentrations, termed "heavy metals." Soft shell clams sampled from areas with heavy-metal pollution grow significantly more slowly than clams in unpolluted areas,[3] and are in generally poor condition,[57] but recovery is rapid when heavy-metal pollution ceases.[3] Table 3 lists some of these metals and their measured toxicities. Compared to other aquatic organisms, soft shell clams are particularly vulnerable to copper and mercury. Copper is bioaccumulated slightly more in low salinity than in full seawater,[183] so soft shell clams in Chesapeake Bay are particularly vulnerable.

Tributyltin (TBT), until recently a component of most marine antifouling paints (its use on large vessels continues), is believed to be extremely toxic to most marine organisms, and is bioaccumulated at high rates by filter feeders such as soft shell clams.[93] The toxicity of organotins to soft shell clams has not been studied.

Metallic aluminum particles are apparently nontoxic to soft shell clams.[63]

Pesticides, Chlorine, Polychlorinated Biphenyls

A variety of pesticides, including DDT, endrin, dieldrin, and endosulfan have been shown to be toxic to soft shell clams, but recovery is rapid when exposure ends.[141] Chlorine-produced oxidants, a byproduct of sewage treatment, in concentrations as low as 0.3 mgL^{-1} kill 50% of soft shell clam larvae with only 16 hours of exposure.[142]

Polychlorinated biphenyls (PCB), formerly used in many industrial products, have been suggested as causes of poor condition in soft shell clams from polluted areas.[57] Even in highly polluted areas, however, such as the Elizabeth River in Virginia, low populations of adult soft shell clams persist.[140]

Petroleum and Petroleum Products

Petroleum, both crude and refined, and its by-products, including polycyclic aromatic hydrocarbons (PAH), are toxic to soft shell clams. Oil spills can be particularly damaging. In muddy sand, such as that found in Chesapeake Bay, spilled oil penetrates slowly but remains for years, and destroys increasingly larger clams over time, eventually eliminating most of the population.[40] Clams transplanted to oil spill areas also die out due to the oil.[39] Depending on the dose and the type of oil, the growth rates of survivors are significantly reduced. Bunker C and Number 6 fuel oil have been shown to reduce growth by as much as 50% in survivors.[3,58,59,104] Hydrocarbons extracted from polluted sediments are more than ten times as toxic to soft shell clams as they are to fish.[168] Not all oil pollution has been shown to have adverse effects,[1] but crude oil is bioaccumulated by soft shell clams.[55]

The role of hydrocarbon pollution in diseases of soft shell clams has been debated, but in general high incidences of cancer-like diseases correlate with hydrocarbon pollution. Neoplasia, hyperplasia, and germinoma have all been correlated to hydrocarbon pollution of various types.[7,67,177] Brown *et al.*[20] did not find a correlation with total hydrocarbon pollution, but did find a correlation between neoplasia and total PAH levels. Polynuclear aromatic hydrocarbons have been implicated as carcinogens, and are common components of hydrocarbon pollution. This is an example of an indirect effect of human impact, and there are others which probably go unnoticed.

Bioaccumulation

From a human viewpoint, the most serious aspect of pollution in a fishery species is bioaccumulation. Many pollutants are bioaccumulated, or concentrated, by soft shell clams, some of which are thought or known to be extremely toxic to humans. An indirect danger is that sublethal quantities of toxicants will be accumulated further by predators of soft shell clams, such as blue crabs, which are also fishery species.

Two studies on soft shell clam bioaccumulation of heavy metals and organochlorine residues in Maryland[46,47] showed no dangerous levels, but all compounds examined were bioaccumulated to some extent. Soft shell clams bioaccumulated most of the toxicants less than or equally to oysters, but arsenic, which was increasing in sediments, was bioaccumulated more than by oysters. Mercury and cadmium were not bioaccumulated in high amounts, probably because of their toxicity to soft shell clams. However, blue crabs, which feed on soft shell clams, showed greater accumulation of these metals.

Tributyltin is accumulated by soft shell clams far more than by non-filter feeders, and over 50 times more than by sediments.[93] A pesticide (diquat) however, was present in lower amounts in soft shell clams than in sediment.[68] Chrysene, DDT, and napthalene were not bioaccumulated from sediments; diethyl ether and dioctyl phthalate were accumulated from sediments only in trace amounts,[56] but this did not mean that they were not bioaccumulated from the water. Butler[23] found that soft shell clams accumulate all pesticides tested (aldrin, DDT, dieldrin, endrin, heptachlor, lindane, and methoxychlor) to a greater extent than hard clams but also decreased their body burdens better than hard clams when exposure stopped. Both crude oil and PAHs are bioaccumulated by soft shell clams, even when levels in the water are very low.[58,118] Copper and zinc, on the other hand, are accumulated far less than by oysters.[114]

Diseases

Soft shell clams in the Mid-Atlantic Bight area are subject to a variety of cancer-like diseases, which may be directly due to a viral agent.[30] The agents of these diseases are not known, and there are no standard descriptions of most of them, but at least four cancer-like diseases have been described. These include: neoplastic proliferation of tissue (usually mantle) that invades other tissues; hematocytic neoplasia, or leukemia,[158] an extreme increase in the number of hemolymph cells; hyperplasia, or proliferation of gill tissue; and germinoma, or proliferation of gonadal tissue [67,177].

Only one of these diseases, described as an epizootic sarcoma, and probably synonymous with neoplasia, has been studied in Chesapeake Bay. It was implicated in mass mortalities in parts of the Maryland Eastern Shore, where up to 65% prevalence was found in sampled populations, with 100% mortality of diseased clams.[52] Hematocytic proliferation, however, has been found with up to 40% incidence in Rhode Island, with 50% mortality of diseased clams.[29]

Other diseases include hypoplasia, or defective gonadal development, and lipofuscin deposits, or brown pigmented areas.[177] No mortalities have been reported for hypoplasia, but if the incidence is high, a significant proportion of the population effectively could be castrated. Lipofuscin deposits are not known to be pathogenic, but are more prevalent in polluted areas.[21] The role of pollution in many of the above diseases, especially neoplasia, is fairly well established. Although pollution may not cause these diseases, certain forms of pollution are well-correlated with incidence of neoplasia[7,20,21,67,177] as discussed below.

A series of soft shell clam mass mortalities in 1970 and 1971 in Maryland led to an investigation of pathogenic bacteria, and eight pathogenic bacteria were discovered. Whether any of these caused the mortalities is not known, but it demonstrated that bacterial diseases may be important ecological factors in soft shell clam populations.[85] The role of disease in regulating soft shell clam populations has not been studied widely, but existing information suggests that diseases of all sorts may be as important as environmental factors or predators in adult clam population dynamics.

The most alarming soft shell clam pathogen from a human viewpoint is paralytic shellfish poisoning, caused by the planktonic dinoflagellate *Alexandrium (Gonyaulax) tamarensis.* This species is apparently toxic to soft shell clams, which reduce feeding and reject the dinoflagellates when they are present. For this reason, up to ten days after the start of a bloom there is no significant accumulation of the algal toxins by soft shell clams.[152] Fortunately, *A. tamarensis* does not bloom frequently in Chesapeake Bay. Paralytic shellfish poisoning therefore is not considered a problem in this location.

Although parasites probably are present, they have not been studied in soft shell clams in Chesapeake Bay. Probably the most serious parasite is the cercaria stage of the trematode *Himasthia leptosoma,* which replaces muscle tissue in clams (mud snails and various shore birds are hosts for the parasite's other life stages). A number of other trematode species have been identified in soft shell clams in New England and Canada.[28] A turbellarian flatworm has been found in soft shell clams, but apparently it is not clear whether it is parasitic. The commensal nemertean *Macrobdella grossa* probably is not parasitic. A ciliate protozoan has been identified as a parasite, but does not appear to be common.[28] Two copepods have been identified as occasional parasites in soft shell clams. The parasitic pea crab is strictly polyhaline,[182] as are the ectoparasitic snails,[179] so they do not affect most soft shell clams in Chesapeake Bay.

Sewage and Eutrophication

Soft shell clam populations can persist in areas with high domestic pollution,[78] but a high organic content, characteristic of sewage-polluted sediments, correlates with reduced growth rate of soft shell clams.[120] One effect of sewage, however, is eutrophication, which can enhance regional anoxia.

So far eutrophication has not been a problem for Chesapeake Bay soft shell clam populations. Evidence from Sweden indicates that domestic sewage can enhance eutrophication catastrophically, leading to widespread anoxia with total eradication of infauna (including soft shell clams), so the danger probably exists in Chesapeake Bay.

Disturbance

Heavy siltation can occur from dredging operations or storms. Survival of adult soft shell clams buried by sediments varies with the kind of sediments. Burial by up to 24 cm of coarse, mud-free sand can be survived, but only 6 cm of fine sand and only 3 cm of silt can be fatal.[169] New channels occasionally are dredged in shallow areas, e.g., for creation of marinas, with obvious direct effects on any clams in the path of the channel. But most often existing channels, which do not support significant clam populations, are deepened or widened. If the dredged material is very fine, much of it may drift over adjacent areas and bury soft shell clams, which are susceptible especially to burial by fine sediment.

Hydraulic escalators, used to harvest soft shell clams in Chesapeake Bay, do relatively little damage to surviving clams. Incidental mortality of unharvested clams is about 7%, incidental catch of fish and crabs is largely nonlethal, and oysters more than 30 m away are unaffected.[106,115,134] This compares to about 50% mortality of unharvested clams by hand methods used in New England.[116] Delicate burrow systems and submerged aquatic vegetation are totally eradicated by the hydraulic harvesters, however.[106] The use of the hydraulic dredge has been reviewed by Kyte and Chew.[90]

Intertidal populations of soft shell clams are the only significant pool of adults in some parts of Chesapeake Bay,[69,102] so destruction of intertidal areas by shoreline construction, erosion, landslides, or other factors can have a disproportionally large effect on soft shell clam populations. Conversely, landslides can help create habitat for soft shell clams in the intertidal and shallow subtidal regions of the Bay if they replace unsuitable sediment with suitable sediment. The effects of shoreline destruction, as well as bottom disturbance, by wakes and propeller wash from the increasing number of recreational boats, has not been studied in this context, but at this point effects are probably minor and local.

Power Plants

"Extensive" mortalities of soft shell clams were reported in the Patuxent River in Maryland after the Chalk Point power plant was constructed, presumably due to heated effluent.[117] Studies specifically designed to study the effect of heated water near Calvert Cliffs, Maryland, however, failed to show any harmful effects to soft shell clams.[76,77,99] This is a complex issue, in part because spawning, which is temperature-related, may also be affected by heated effluent.

CONCLUSIONS AND RECOMMENDATIONS

Harvesting

The fertilization and settlement patterns of soft shell clams described above suggest that as long as each subestuary has reserved a small but sustained pool of adult soft shell clams, and as long as care is taken not to destroy newly settled clams by disturbance or sedimentation, harvesting will have no long term population effects. Since denser populations probably have better spawning success, for optimum effect the reserve population of adults in each subestuary should be in an area that traditionally sustains high densities of adults. Since domestic sewage apparently has no serious direct effects on soft shell clams, one possibility is to use areas condemned for shellfish harvesting because of domestic sewage as adult reserve areas.

Although hydraulic escalators used to harvest soft shell clams in Chesapeake Bay do relatively little damage to unharvested soft shell clams or incidental catches of mobile fauna, submerged aquatic vegetation and oyster reefs are destroyed completely. The preservation of submerged aquatic vegetation and oyster reefs, because of their importance in the ecology of Chesapeake Bay, should in all cases take precedence over soft shell clam harvesting; however, harvesting can occur within about 100 m of these communities with little harm.

Pollution

Because copper is the most deadly heavy metal to soft shell clams, any pollution monitoring in areas where soft shell clams are a concern should include measurements of copper ion concentrations.

Because oil spills lead to massive clam mortalities and, in areas with sublethal pollution, cause reduced growth rates, measures to protect the Bay from oil spills are important to preserving soft shell clam habitat.

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Table 1. Predators on juvenile soft shell clams in the Chesapeake Bay.

Major Predators	Minor Predators
Polychaete worm (*Nereis virens*)[73,96]	Flatworm (*Stylochus ellipticus*)[91]
Blue crab (*Callinectes sapidus*)[97,176]	Polychaete worms (Eunicidae, Nephtyidae Nereidae)[53,96]
Mud crabs (Xanthidae)[65,69,104,181]	Mud snails (*Ilyanassa obsoleta, Nassarius* spp.)[69,80]
Shrimp (*Crangon septemspinosa*)[6,137]	Moon snail (*Polinices duplicatus*)[44]
Mummichogs (*Fundulus* spp.)[74,86]	Oyster drills (*Urosalpinx cinerea, Eupleura caudata*)[24]
Spot (*Leiostomus xanthurus*)[74,76,77]	Horseshoe crab (*Limulus polyphemus*)[13,14]
	Amphipods (Gammaridae)[50]
	Snapping shrimp (*Alpheus* spp.)[8]
	Hermit crabs (*Pagurus* spp.)[6]
	Croaker (*Micropogonias undulatus*)[74]
	Winter flounder (*Pseudopleuronectes americanus*)[6,94]
	Tautog (*Tautoga onitis*)[10]
	Ducks (*Anas* spp., *Aythya* spp.)[61,83]

Table 2. Predators on adult soft shell clams in the Chesapeake Bay.

Major Predators	Minor Predators
Blue crab (*Callinectes sapidus*)[97,176]	Ribbon worm (*Cerebratulus lacteus*)[84]
Eel (*Anguilla rostrata*)[180]	Moon snail (*Polinices duplicatus*)[45,79]
Cownose ray (*Rhinoptera bonasus*)[126,155,156]	Whelks (*Busycon* spp.)[38]
	Skates (*Raja* spp.)[74,155]
	Rays (*Dasyatis* spp.)[74]
	Black drum (*Pogonias cromis*)[74]

Table 3. Toxicity of metals to soft shell clams: LC_{50} is the concentration that is lethal to 50% of the sample in a 7 day time period. Data from Eisler[48] and Eisler and Hennekey.[49]

Metal	LC_{50} (mgL^{-1})	Metal	LC_{50} (mgL^{-1})
Cadmium (Cd^{2+})	0.15-0.7	Manganese (Mn^{2+})	300
Chromium (Cr^{+6})	8.0	Mercury (Hg^{2+})	0.004
Copper (Cu^{2+})	0.035	Nickel (Ni^{2+})	30
Lead (Pb^{2+})	8.8	Zinc (Zn^{2+})	3.1