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A STUDY OF THE ARKSHELL CLAMS, *NOETIA PONDEROSA* (SAY 1822) AND *ANADARA OVALIS* (BRUGUIÈRE 1789), IN THE OCEANSIDE LAGOONS AND TIDAL CREEKS OF VIRGINIA

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ABSTRACT Two species of arkshell ("blood") clams, *Noetia ponderosa* and *Anadara ovalis*, have recently been targeted by watermen on the eastern shore of Virginia for sale to both East and West Coast markets in the United States. Until 1991, fishermen caught both species in the harvest of oysters and hard clams, and discarded them as bycatch with little value. Very little is known about either species of blood clam, and preliminary data from a pilot study in 1993 indicated that they were being over-fished. We conducted a survey in September 1994 in the oceanside lagoon system along the eastern shore of Accomac and Northampton Counties, Virginia, and collected data on density, abundance, habitat preference, age-size and morphometric relationships, and mortality rates for both species of blood clams, as well as some ancillary data on the hard clam, *Mercenaria mercenaria*. The study provides baseline data for establishing management practices and regulations for the blood clam fishery. The total estimated abundance in the study area was about 16 million *N. ponderosa* and 6.4 million *A. ovalis*. Of the clams taken in commercial catches on the oceanside of the eastern shore, *M. mercenaria* constitutes about 84%, *N. ponderosa* 15%, and *A. ovalis* 1%. In our field survey, *M. mercenaria* was the most abundant species (72% of the total catch), followed by *N. ponderosa* (17%) and *A. ovalis* (11%). Densities for blood clams averaged 0.35 clams m^{-2}, or 3,500 clams per hectare, and were highest in shell and shell/mud substrate (1.1 and 1.2 clams m^{-2}, respectively). Growth studies and age-size data show that *A. ovalis* grows about twice as fast as *N. ponderosa* and that market-size *N. ponderosa* (about 56 mm in shell height) may be 8+ years old. We also present information on mortality rates and morphometric relationships for both species of blood clams, and recommendations for maintaining and enhancing the fishery.

KEY WORDS: Noetia ponderosa, Anadara ovalis, arkshell, blood clam, growth rate, density, substrate

INTRODUCTION

Since 1991 two species of arkshell or "blood" clams, *Noetia ponderosa* (Say 1822) (ponderous ark) and *Anadara ovalis* (Bruguière 1789) (blood ark), have been harvested by watermen on the eastern shore of Virginia for sale to markets in Washington D.C., New York City, Los Angeles, and Chicago. Long considered a useless incidental catch in the harvest of the hard clam, *Mercenaria mercenaria* (Linnaeus 1758), and the eastern oyster, *Crassostrea virginica* (Gmelin 1791), arkshell clams now constitute a rapidly growing fishery with potential for future development. However, there is very little published information on the life history of either of these species. Chanley (1966) and Chanley and Andrews (1971) described the larval stages of *N. ponderosa* and *Anadara transversa* (Say 1822) in Virginia waters and reported spawning periods of June to December and May through September, respectively. In addition, they stated that *A. transversa* was common in Chesapeake Bay and tributaries with salinities above 15. Loosanoff and Davis (1963) and Loosanoff et al. (1966) also described the larval development of *A. transversa*. McGraw and Castagna (1994) conducted preliminary investigations on growth rates of *A. ovalis* and *N. ponderosa* on the eastern shore of Virginia concurrent with the growth of a blood clam fishery there. Anderson et al. (1985) also reported the potential for a viable blood clam fishery along the South Carolina coast but could not find a market for the clams. Walker (1998) studied the growth and survival of *A. ovalis* in suspended pearl nets in Wassaw Sound, Georgia. The intensive harvesting of blood clams and paucity of data on important factors such as distribution, densities, growth rates, and sur-

vival present a problem for management of the fishery in Virginia waters.

Blood clam landings in Virginia (Fig. 1) from 1993 to 1998 (National Oceanic and Atmospheric Administration 2000) show that about 8.9 metric tons of blood clams were harvested in 1993, with a decline to 2.5 metric tons in 1995, and an increase to 10.8 metric tons in 1997. The most logical explanation for the resurgence in tonnage appears to be a change in gear type, from mostly mechanical tongs during the early phase of the fishery to clam dredges after 1996. Landings are reported as wet-meat weights, whereas the clams are usually sold whole, in the shell. Using a conversion factor supplied by the state of Virginia (Iverson pers. comm., Virginia Marine Resources Commission, February, 2000), we estimated that the number of clams range from about 340,000 clams landed in 1995 to 1.5 million clams in 1997.

Most of the blood clams harvested along the eastern shore of Virginia are *N. ponderosa*; however, some *A. ovalis* are included, and buyers make no distinction between the two species. Virginia State fishery regulations concerning the harvest of arkshell clams are currently the same as for hard shell clams, and prohibit dredging from April 1 through December 1. Harvest by mechanical tongs is not regulated by season, and that method is used to continue harvesting during the closed dredging season. Clam fishermen would like to harvest blood clams by dredging year-round to provide consistent supplies to the markets they have developed. They requested a variance from the fisheries regulatory agency, Virginia Marine Resources Commission (VMRC), to permit dredging the arkshell clams during the normally closed season (Terry 1991). However, VMRC denied the request until more information was available on which to base management practices and regulations.

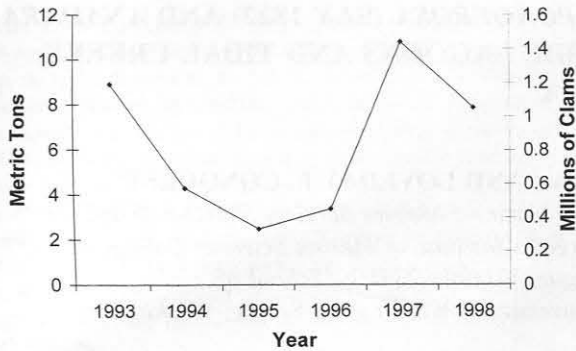*Corresponding author. E-mail: kay.mcgraw@noaa.gov

Figure 1. Blood clam landings in Virginia, 1993–1998 (National Oceanic and Atmospheric Administration/National Marine Fisheries Service, http://www.st.nmfs.gov/commercial/index.html).

The number of blood clams sold in retail markets in different regions is difficult to obtain, but two seafood dealers in Washington, D.C. offered some estimates for their stores. One sold 3,000 to 5,000 per week at a price of $2.50 to $3.00 (U.S.) per dozen (Pruitt pers. comm., Washington, D.C., 1993). Another company sold about 2,000 blood clams per week from about November through March for about $3.00 to $4.00 per dozen (Martin pers. comm.,Washington, D.C., 1993). Prices usually range from $0.11 to $0.18 per clam (Bishop pers. comm., Oak Hall, VA, 1996); however, watermen reported receiving from $0.07 to $0.25 per whole clam, depending on the size and demand. One reportedly received $0.50 per clam by selling the clams directly from his boat (Annis pers. comm., Willis Wharf, VA, 1993).

Blood clams from Virginia are sold primarily in ethnic markets in the U.S. and are eaten raw and cooked. Both species have a somewhat bitter taste and contain the blood pigment hemoglobin, which gives the flesh a blood-red color (Abbott 1968, Yonge and Thompson 1976). These attributes may explain why they are not usually eaten in the U.S.; however, various ark species (also called blood cockles in some countries) constitute significant fisheries in many other parts of the world, including China, West Africa, Japan, Mexico, Tanzania, India, Thailand, Malasia, and Taiwan (Bae 1986, Baqueiro 1980, Broom 1983, Broom 1985, Guo et al. 1999, Ismail 1986, Kayombo 1993, Narasimham 1969, Narasimham 1988, Nie 1990, Sahavacharin et al. 1988, Ting 1984, Wong and Lim 1985). Prior to 1950 there were also substantial harvests of Arca noae (up to 685 tons per year) from the Adriatic Sea (Hrs-Brenko 1980).

The ponderous ark (N. ponderosa) has a heavy, thick shell, is ubiquitous along the oceanside of the eastern shore of Virginia, and aggregates in shell debris or "shell hash" where juveniles attach by a prominent byssus to whole shells and pieces of shell (McGraw and Castagna 1994, McGraw et al. 1996). This species ranges from Virginia to the Florida Keys and in the Gulf of Mexico from Key West to Texas. Virginia is thought to be the northernmost extension of the range, and shells found north of Virginia are probably fossils (Abbott 1954). Because they have no siphons, as some other clams do, ponderous arks are usually found at the substrate surface, making them very accessible to dredges and tongs. Market sized N. ponderosa may include animals over ten years old (McGraw et al. 1996).

The blood ark (Anadara ovalis) is found from Cape Cod to the Gulf of Mexico, the Caribbean, and West Indies (Abbott 1954, Gosner 1978) and occurs subtidally from shallow water to 45 m both in shell and muddy substrates. It has a much thinner shell than the ponderous ark. In salinity tolerance studies, Castagna and Chanley (1973) found that A. ovalis and N. ponderosa generally functioned better in salinities exceeding 20.

The primary purpose of our study was to gather data on the growth rate, size-frequencies, ages, densities, abundance, and survival of blood clams on the eastern shore, and to make these data available to fisheries management agencies for consideration in overseeing the fishery. Unlimited harvesting, coupled with the slow growth rate of N. ponderosa and insufficient recruitment, could eventually lead to depletion of blood clam populations if present harvest practices persist.

METHODOLOGY

The study consisted of four main parts: (1) conducting a field survey to obtain data on density, substrate preference, distribution, abundance, and mortality rates for the two species of blood clams in the tidal lagoons of the eastern shore of Virginia; (2) determining growth rates from age-size relationships using the acetate peel technique; (3) collecting fisheries catch data from local watermen; and (4) following the growth rates of cohorts of A. ovalis and N. ponderosa over a 2-y period. Although the primary emphasis of the study was on blood clams, we collected some data for the hard clam (Mercenaria mercenaria), and some of that information is also included for comparison, since it is the primary species harvested.

Field Survey

We conducted a field survey aboard a commercial fishing vessel rigged with mechanical tongs during September 1994. The main sampling area (Fig. 2) was the oceanside of the eastern shore of Virginia from the Great Machipongo Inlet to Wachapreague Inlet, or the general area between longitudes 75°42'–50'W and latitudes 37°20'–38'N. We employed both random and systematic sampling techniques, depending on the area being sampled. In Hog Island Bay, depth of water permitted more random sampling, both in channels and over mud flats, whereas the more northern part of the study area was better suited to systematic sampling in channels.

We determined random sampling sites by setting up a grid overlay (800 m × 800 m blocks) of the Hog Island Bay area (NOAA chart #1221) and used random number tables to determine which blocks we would sample. We took three samples within each chosen block, and the sampling locations within the block
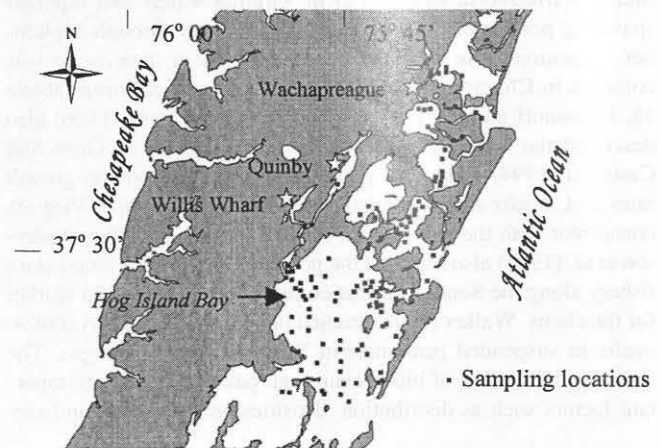

Figure 2. Map of study area.

constituted one station. If water depth in a block was too shallow, we eliminated the sampling site and selected additional random numbers until another suitable block was chosen.

In addition to the blocks chosen by random numbers, we included portions of some of the following tidal creeks and channels in a systematic sampling plan: Swash Creek, Sandy Creek, Sloop Channel, Parting Creek, Machipongo River, Great Machipongo Channel, Quinby Inlet, Sand Island Channel, Millstone Creek, and Wachapreague Inlet. In tidal creeks and channels we took three samples approximately every 0.5 miles or 900 m, usually in the immediate vicinity of channel markers to more precisely locate positions on navigation charts. Channel samples usually spanned the channel or creek along transects, with one sample from the middle and one from each side. We sampled a total of 119 stations.

We used mechanical tongs for sampling gear instead of a dredge because tongs cover a discrete area, 1.12 m², penetrate into the substrate about 15 cm, and retain more substrate when retrieved from the bottom. Retention of substrate and small clams was assured by lining the tongs with 1 cm² plastic mesh. Area is a more pertinent measurement than volume for assessing densities of blood clams because the clams inhabit the upper 6–8 cm of substrate and are easily caught with tongs. We placed samples in plastic bags or buckets and sorted them on shore.

We processed samples on shore by washing them through 1 cm² mesh screens (corresponding to the mesh size lining the tongs) and counted and measured all clams (height, length, and depth) to the nearest mm with vernier calipers. Height is defined as the distance between the dorsal hinge (umbo) and the ventral lip of the clam (Fig. 3), and length is the distance from the anterior end to the posterior end. Depth or thickness is the greatest distance between the right and left valves. We used morphometric data to construct size-frequency distributions for both species of blood clams as well as to determine relationships between height, length, and depth for *N. ponderosa* and *A. ovalis*. We also weighed some clams to determine the correlation between height, whole weight, and wet meat weight.

Our preliminary observations (McGraw and Castagna 1994) indicated that *N. ponderosa* is found almost exclusively in areas with shell and shell debris. Because random survey samples contained varying substrates, we could evaluate habitat preferences for *N. ponderosa* and *A. ovalis*. We qualitatively placed substrate material in each sample into the categories used by Haven et al. (1981) (i.e., mud, sand, shell, shell/mud, shell/sand, and sand/mud) and provided areal estimates of each. Space limitations of the vessel and the volume of substrate in some samples dictated that only portions of samples (i.e., sub-samples) be retained for sorting. In those instances, we noted sub-sample proportions, along with other data, and factored those into the density calculations during data analyses to obtain adjusted densities. We estimated densities for each species at each station based on the number of clams obtained per sample and surface area covered by the tongs (i.e., approximately 1.12 m²).

Analysis of field data showed that the general distribution of clams was clustered or aggregated (i.e., non-normally distributed), as evidenced by coefficients of dispersion > 1 (Sokal and Rohlf, 1969). Therefore, we transformed density data using log (X + 1) transformation according to the method discussed in Zar (1974) and Sokal and Rohlf (1969) before we applied analysis of variance (ANOVA) or other statistical tests (e.g., to test for differences between mean densities among substrate types). After transformation, we calculated clam densities by dividing the number of clams
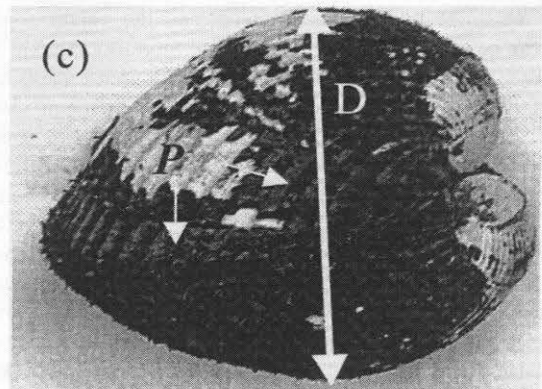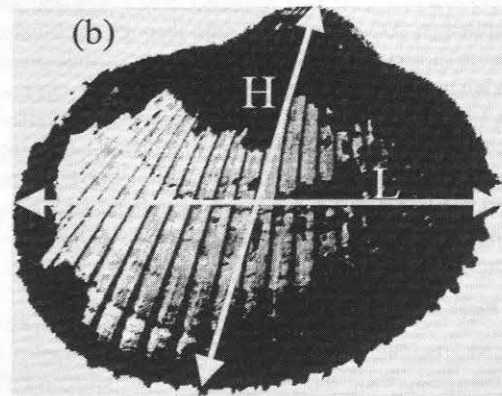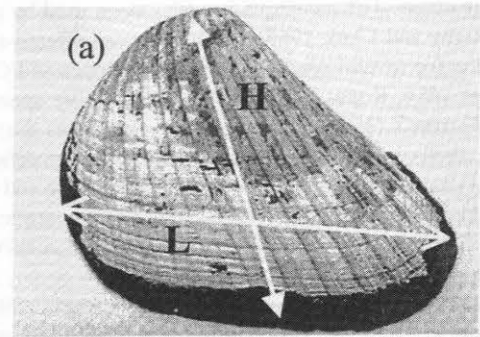

Figure 3. *Noetia ponderosa* (a) and *Anadara ovalis* (b) showing length (L) and height (H) dimensions; (c) *Anadara ovalis* showing depth (D) dimension and periostracum layer (P).

caught in each sample by the area covered by the mechanical tongs (i.e., 1.12 m²). Then we tested mean densities of clams (both species combined) found in the various substrates using ANOVA (Sokal and Rohlf 1969) and the Student-Newman-Keuls (SNK) test (Zar 1974) to determine which means, if any, were significantly different ($\alpha = 0.05$). We analyzed data further according to substrate type and water depth (i.e., deep water/channels or mud flats/shallow areas).

Where substrate type was the same for two or three samples from a station, we averaged those for each station; if substrate types differed, we treated them as separate samples. Therefore the number of samples for comparing species by substrate types was 169 instead of 119.

Shell Aging

We used acetate peels on different sizes of blood clams to determine age more precisely and to estimate the maximum lon-

gevity of the clams. The technique has long been used by paleon-tologists (Rigby and Clark 1965), but has proven effective in age determination for several species of bivalves (Ropes and O'Brien 1979, Ropes 1984, Ropes 1987, Kennish 1980). We specifically employed Farrow's (1971) method, which eliminates the step of embedding shells in epoxy resin. In addition, we modified Far-row's (1971) method by using thick (1.56 mm) acetate and cutting it into 7.6 cm × 2.54 cm pieces (i.e., the size of microscope slides) that could fit easily onto the mechanical stage of a compound microscope.

Several authors have discussed shell microgrowth patterns in detail, including Pannella and MacClintock (1968), Rhoads and Pannella (1970), and Lutz and Rhoads (1980). Age and size data can be applied to size distribution data through back-calculation procedures to create age frequency distributions, thus providing a better understanding of the population structure (Robson and Chapman 1961, Gulland 1966, Ricker 1975). We determined ages for all blood clams from the field survey and increased sample size and accuracy by supplementing these with data from previous studies and additional clams purchased from local watermen. Then we constructed Von Bertalanffy growth curves (Ricker 1975) for both species of blood clams.

Mortality Rates

We used articulated clam shells from survey samples to esti-mate annual age-specific and instantaneous mortality rates for both species. Some bivalves remain articulated for a time after death before the hinge ligament deteriorates and the valves separate. These can be used to help estimate natural mortality (Dickie 1955, Buckner 1984) by dividing the number of articulated shells by the sum of live clams plus articulated clams for different size/age groups. There are no data documenting the length of time for deterioration of the hinge ligament for either *N. ponderosa* or *A. ovalis* in Virginia waters, and all mortality rate calculations are based on an assumed time period of one year for disarticulation. We computed instantaneous mortality rates using the equation (Z) = $-\log E (1 - A)$, where A = the number of living clams in an age group and E = 2.718, the base of natural logarithms (Ricker 1975). First, we applied age-length data from acetate peels to the size distribution of living and articulated clams from the survey and determined the number of clams in each age-size class. Then we divided the number of articulated shells in a given age-size category by the number of live clams to arrive at an age specific or annual mortality rate expressed as a percentage.

Commercial Catch Data

Mr. David Bishop (Oakhall, VA, Accomac County) collected and recorded data on the proportion of blood clams versus hard clams from many of his tong catches over a three-month period, from September through November, 1994. We used height-frequency data from his catches for comparison with data from 1993 fisheries samples to help determine if average clam size in commercial catches was decreasing and also to more accurately assess the percentage of blood clams in clam harvests.

RESULTS AND DISCUSSION

Field Survey Results

Clam Density and Abundance

We took a total of 355 individual samples at 119 stations, which yielded adjusted totals of 86 *N. ponderosa*, and 55 *A. ovalis*.

The 119 stations included random stations, mostly in Hog Island Bay, as well as non-random, or systematic stations, in the northern part of the study area, taken mostly in channels or creeks. Before combining data from all stations, we first ascertained (using trans-formed data and ANOVA) that there was no significant difference (α = 0.05) in mean clam densities (total densities or by species) between random and non-random stations.

For the non-random (mostly channel) stations, we also tested to see if there was any correlation between clam densities and station location within particular waterways, as defined by distance (nau-tical miles) from the entrance of a channel (Scheaffer et al. 1996). We found no correlation or trends (maximum r^2 = 0.06 in the Great Machipongo Channel) and combined all non-random chan-nel stations for further analyses.

Average density (mean ± standard error = $\bar{X}$ ± S.E.) at all stations (n = 119) was 0.21 ± 0.06 clams m^{-2} for *N. ponderosa* and 0.14 ± 0.07 clams m^{-2} for *A. ovalis*. Total average blood clam density was 0.35 ± 0.10 clams m^{-2}. Compared to hard clams, 17% of the total catch was *N. ponderosa* and 11% was *A. ovalis*.

To compare densities by substrate, we averaged densities for each substrate at each station; if station samples contained two or more different substrates, those were considered separate samples. We did this to minimize any pseudoreplication (Hurlbert 1984) and to avoid combining samples across substrates. Therefore, sample size for comparing substrates was 169 (i.e., at some sta-tions not all samples were of the same substrate). In addition, because the mean densities are weighted differently when catego-rized by substrate type, they are slightly different from those cal-culated for stations, where the sample size was 119. The propor-tion of different substrate types among stations was as follows: mud = 35%, n = 59; sand = 11%, n = 18; sand/mud = 21%, n = 36; shell/mud = 17%, n = 29; shell/sand = 6%, n = 11; and shell = 10%, n = 16.

Mean clam densities varied among substrate types (Fig. 4) and were highest in shell (1.24 ± 0.4 clams m^{-2}) and shell/mud sub-strates (1.12 ± 0.49 clams m^{-2}). *Noetia ponderosa* accounted for most or all clam densities in those two substrates. For example, mean density of *N. ponderosa* was highest in shell/mud substrate (1.12 clams m^{-2} ± 0.49) and shell (0.79 ± 0.36), whereas *A. ovalis* densities were highest in shell substrate (0.45 ± 0.24 clams m^{-2}) and mud substrate (0.19 ± 0.15). The highest density of *N. pon-derosa* we observed in a single sample was 13.4 clams m^{-2} at a station in the Great Machipongo Channel (intracoastal waterway); the mean density at that station was 4.46 clams m^{-2}. The highest
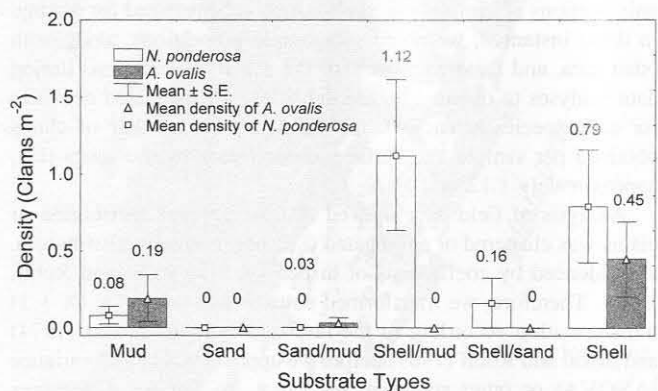

Figure 4. Comparison of *A. ovalis* and *N. ponderosa* densities (clams m^{-2}) in various substrates from the eastern shore of Virginia.

density of *A. ovalis* was 15.0 clams m^{-2} from a sample in The Deeps Channel, a branch of the Great Machipongo Channel.

After transforming density (i.e., log [X + 1]), we compared mean blood clam densities for the six substrate types using ANOVA ($\alpha = 0.05$) and the Student-Newman-Keuls test (Zar 1974) to determine which, if any, means were different. There was a significant difference in mean total blood clam densities among substrates ($P < 0.001$). There were no significant differences in mean total blood clam densities between shell and shell/mud substrates, or between mud substrate and shell/sand, sand/mud, or sand (Table 1 and Fig. 4). However, there were significant differences in mean densities between both shell or shell/mud substrates and all other substrate types ($P < 0.001$). Results are summarized as follows: (shell = shell/mud) ≠ (mud = shell/sand = sand/mud = sand).

Next, we compared densities for both species by substrate type. Results were the same for analyses of *N. ponderosa* densities by substrate types as for both species combined. However, density of *A. ovalis* in shell substrate was significantly different from those in all other substrates, i.e., shell ≠ (shell/mud = mud = shell/sand = sand/mud = sand). The higher densities of clams in shell and shell/mud substrates suggests that shell is important either for attachment, protection from predation, or both.

We estimated the abundance of clams (Table 1) by using substrate data from Haven et al. (1981) and multiplying the density of clams found in various substrates by the number of hectares of that substrate for the study area. That is, $A_t = \sum (Ds \times ha)$, where A_t = the total abundance of clams in the study area; Ds = the total mean density of clams in a given type of substrate; and ha = number of hectares of a given substrate in the study area. Haven et al. (1981) estimated the following amounts (converted to hectares here): shell = 116 ha; shell/sand = 838 ha; shell/mud = 1,002 ha; sand = 1,523 ha; mud = 2,933 ha; sand/mud = 1,057 ha. The combined areal totals from Haven et al. (1981) are for Burton's Bay, Bradford Bay, Swash Bay, Upshur Bay, Major Hole Bay, Revel Island Bay, Hog Island Bay (above and below North Channel), Ramshorn Bay, and Sand Shoal Channel. Total estimated blood clam abundance in the study area (Hog Island Bay, Burton's Bay, and Bradford Bay and contiguous waterways) was 22 million blood clams. Total estimated abundance by species is as follows: *N. ponderosa*, about 16 million; *A. ovalis*, about 6 million. The proportions are based on those from the field survey (Table 1) in which *N. ponderosa* had an average density of 0.31 clams m^{-2} ±

0.09 (n = 169), and *A. ovalis* of 0.12 clams m^{-2} ± 0.06 (n = 169) over all substrates.

We examined clam densities in relation to water depth (i.e., channels or mudflats). Of the 119 stations sampled, 67 were in channels or locations with a water depth >2 meters, and 52 were over mudflats, or in shallow water. Using log transformation and Student's *t*-test (Zar 1974), we determined that there was no significant difference ($\alpha = 0.05$) in mean total blood clam densities (Fig. 5) between channel/deep water stations (0.48 ± 1.3) and mud flat stations (0.19 ± 0.10), even though channel stations had twice the density of shallower ones. The relatively high variances for both means affected results and $P = 0.052$, just slightly more than the stated level of significance.

Although mean clam densities were higher at channel/deep water stations, there were no significant differences ($P > 0.10$) between mean densities in channel and mud flat stations for either species (Fig. 5). One explanation for the higher density of clams in the channels/deep water stations might be that clams are sloughed off or eroded from the sides of the channels, along with substrate, and aggregate in the bottom of the channel. In some of the tidal creeks currents may expose areas of shells, providing more attachment sites for blood clams, particularly *N. ponderosa*.

Size-Frequency

Average shell height for blood clam species (Fig. 6) were: *N. ponderosa*, 42.6 mm (± 2.2, n = 43) and *A. ovalis*, 25.1 mm (± 0.2, n = 29). There were relatively few small *N. ponderosa* (i.e., <25 mm, or about 2 years old) taken in survey samples. This could simply be the result of sampling variability, but could also indicate that recruitment may be low or that mortality rates may be high during the first year after settlement. Most of the hard clams (*M. mercenaria*) in samples were also larger, 60 to 100 mm in height (75.3 ± 1.2, n = 146), and sizes were more normally distributed (Fig. 6c). In contrast, most of the *A. ovalis* (Fig. 6a) were 0+ to 2 years old, with very few older, larger clams in samples.

Articulated Shells and Mortality

After calculating Von Bertalanffy growth curves for both species of blood clams, we applied age-length data to articulated shells, put them into age categories, and estimated annual and instantaneous mortality rates (Table 2) as previously described. In the absence of published or other data on the length of time for

TABLE 1.

Mean densities (m^{-2}) of clams (±S.E.) by species and substrate types, areal estimates of substrate types (from Haven 1981), and clam abundances.

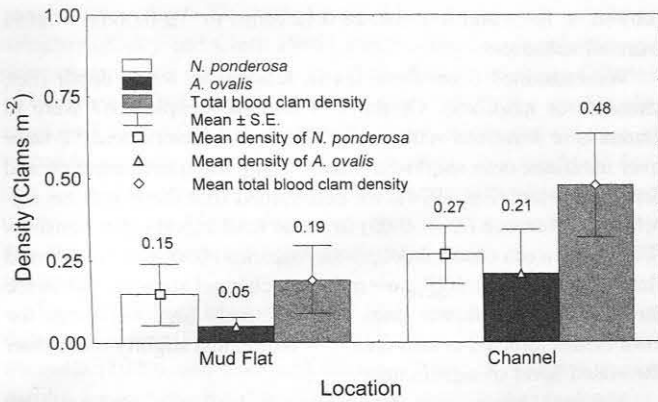| Species	Substrate type						Total avg. density (N = 169)
	Shell (N = 16)	Shell/Sand (N = 11)	Shell/Mud (N = 29)	Sand (N = 18)	Mud (N = 59)	Sand/Mud (N = 36)	
N. ponderosa	0.79 (±0.36)	0.16 (±0.16)	1.12 (±0.49)	0	0.08 (±0.06)	0	0.31 (±0.09)
A. ovalis	0.45 (±0.24)	0	0	0	0.19 (±0.15)	0.03 (±0.03)	0.12 (±0.06)
Total	1.24 (±0.45)	0.16 (±0.16)	1.12 (±0.49)	0	0.27 (±0.15)	0.03 (±0.03)	0.42 (±1.49)
Hectares	116	838	1,002	1,524	2,934	1,057	7,470
Clam abundance (millions)	1.4	1.3	11.2	0	7.9	0.3	22.2

Figure 5. Comparison of blood clam densities (clams m^{-2}) on mudflats and in channels from the eastern shore of Virginia.

disarticulation of shells for either species of blood clam, we assumed a period of one year. Because blood clam density in the study area was relatively low, there were some age groups for which no articulated clams appeared in samples and thus mortality rates were zero. Despite the gaps in data, we think that the mortality estimates provide some insight into basic mortality trends for *N. ponderosa* and *A. ovalis*.

The annual mortality rate (Fig. 7) for 0+ to 1 year *A. ovalis*, calculated using articulated shells in samples, is 86%, then decreases to 30% for the 1+ to 2 year class. Because there were only four articulated clams in the age 3+ category, all less than 48 mm, we pooled the data for a better estimate of mortality rates. The average was 80% for age 3+ clams. Distributed over the estimated maximum life span of six years for *A. ovalis*, the annual mortality rate would be about 27% per year for clams over age 3+. There were no articulated shells in the 2+ to 3 year size range in our samples, so the annual mortality rate for that year class of *A. ovalis* was zero. The increase in mortality rates for older (>3+) clams may be due to senescence or other factors such as disease, or synergistic effects involving spawning and higher water temperatures in the summer. Toyo et al. (1978) (as cited by Broom 1985) reported a sudden mass mortality of a species of *Anadara* (probably *A.*
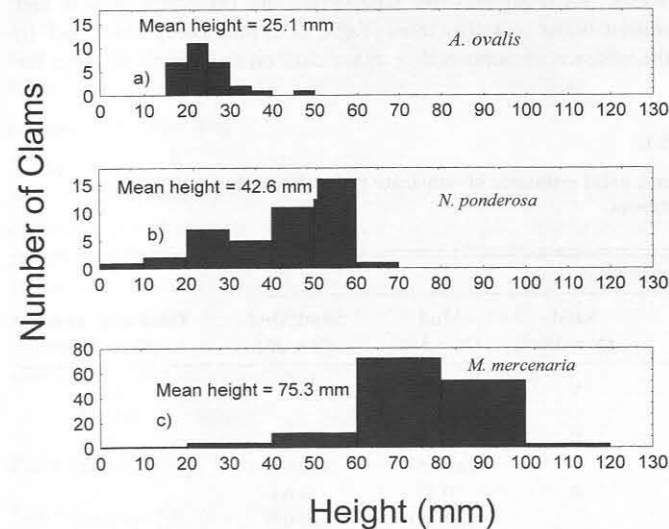
TABLE 2.

Mortality rates (%) and instantaneous mortality rates (Z) for *A. ovalis* and *N. ponderosa*, based on articulated clam shells.

Year class	No. articulated shells	No. live	Total	Mortality (%)	(Z)
A. ovalis					
0–1	70	11	81	86.4	2.0
1+–2	7	16	23	30.4	0.4
2+–3	0	1	1	0.0	0.0
>3+[a]	4	1	5	80.0	1.6
N. ponderosa					
0–1	8	1	9	88.9	2.2
1+–2	3	2	5	60.0	0.9
2+–3	0	9	9	0.0	0
3+–4	0	3	3	0.0	0
4+–5	0	3	3	0.0	0
5+–10[b]	6	11	17	35.3	0.1
10+–15[c]	5	14	19	26.3	0.1

[a] Pooled because of low number of clams in age category. Mortality is estimated to be about 27% per year and (Z) is estimated to be about 0.54 per year for age 3 +– 6 clams.
[b] Mortality is estimated to be about 7% per year and (Z) is estimated to be about 0.1 per year for age 5 +– 10 clams.
[c] Mortality is estimated to be about 5.3% per year and (Z) is estimated to be about 0.1 per year for age 10 +– 15 clams.

broughtoni) in Japan due to a rapid rise in water temperature above 25°C.

Although our estimates are based on relatively few articulated clams, we feel that the data reflect the actual situation, because very few large *A. ovalis* (>50 mm in height) are taken in commercial clam catches and most seem to die before reaching six years of age. A similar phenomenon has been observed for the bay scallop, *Argopecten irradians*, in which about 80% die between months 13–16 (Castagna 1975, Castagna and Duggan 1971). Observations of large *A. ovalis* (i.e., ~53 mm in height) held in flowing water tables indicate that they are sensitive to water temperatures and begin to die above about 27°C, whereas large *N. ponderosa* in the same water tables are not affected. Some watermen have told us that some *A. ovalis* in their catches seem to gape much more readily than *N. ponderosa* during warm weather. It appears that few *A. ovalis* live longer than six years in the Virginia lagoon system, and that mortalities of older clams are exacerbated by high water temperatures.

Figure 6. Height frequency distribution for *A. ovalis*, *N. ponderosa*, and *M. mercenaria*.
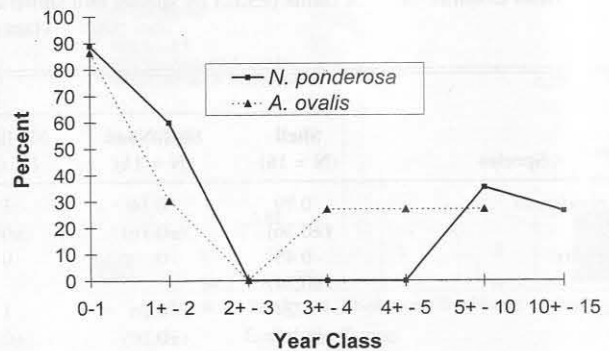

Figure 7. Comparison of mortality rates for *N. ponderosa* and *A. ovalis*.

Walker (1998) reported mortality rates of about 55% for small and medium (<20 mm in length) *A. ovalis* held in pearl nets in Georgia (i.e., from an initial group of 78 clams down to 35) during the first year; average mortality rate for the same groups was about the same during the second year of growth (i.e., 16 out of 35 clams survived). Presumably the pearl nets decreased mortality rates from siltation and predation, and therefore rates were lower than those calculated in our field study. Walker (1998) also stated that the life span for *A. ovalis* in Georgia waters is about three years, whereas we estimated that the life span is six years in Virginia.

Annual mortality rates for *N. ponderosa* (Table 2 and Fig. 7) were highest for the 0+ to 2-year-old groups (89% and 60%, respectively). For convenience sake, and because of small sample sizes, we grouped the 5+ to 10-year-classes and 10+ to 15-year-old clams to determine mortality rates. The cumulative annual mortality rate for the 5+ to 10-year-old group was 35% over the five year period, or about 7% per year; for the 10+ to 15-year-old clams, it was 26%, or about 5% per year.

There were no articulated *N. ponderosa* for the 2+ to 5-y age classes in samples, suggesting a decreasing mortality rate for those age classes. This trend could be a result of increasing size and lower densities during the first two years, as a function of competition for food and space.

Morphometrics

The data used for morphometric relationships are from several sources, including growth studies, fisheries samples, survey samples, and extra clams purchased for shell aging studies. We examined the relationships of several variables: shell height, length, depth, whole weight, and wet weight.

The relationship between valve height and length for *N. ponderosa* (Fig. 8a) is described by the regression equation: $L = 1.22H + 1.73$ ($r^2 = 0.99$) where L = length in mm, H = height in mm, and r^2 = coefficient of determination. Height and shell depth were also linearly related (Fig. 8b) as described by the

regression equation $D = 0.98H - 2.57$ ($r^2 = 0.99$), where D = depth of the clam in mm.

Relationships between height and whole (i.e., shell + meat) or wet meat weights were nonlinear (Figs. 8c and 8d). For example, the relationship of height and whole weight is described by the allometric equation of the form $W = aH^b$ (Fig. 8c) where W = whole weight of the clam in grams, H = height in mm, and a and b are allometric coefficients (a = 0.0006 and b = 3.06). Transformed to the linear form, this equation is: $\log W = b\log H + \log a$. Wet meat weight and height were likewise nonlinearly related by the equation $M = aHb$, where M = meat weight, a = 0.001, and b = 2.52 (Fig. 8d). The coefficient of determination, $r^2 = 0.88$, is slightly lower than that for height and whole weight, since meat weight determinations are subject to more sampling error, mostly because of varying amounts of water loss. Mean shell weight was 46.8 g (± 36.3, n = 132), and mean whole wet weight of *N. ponderosa* was 60.5 g (± 44.06, n = 132), or about 77% of the total weight. Mean meat weight (13.6 g) was about 23% of the total weight of the clams sampled.

Relationships of shell height to length or depth for *A. ovalis* were linear (Figs. 9a and 9b). Unlike *N. ponderosa*, shell length in *A. ovalis* changes little in relationship to the height, and most clams are, as the name ("*ovalis*") implies, oval or nearly round. By comparison, increase in shell depth in *A. ovalis* per increase in shell height is proportionately smaller than that in *N. ponderosa*, in which shell depth is almost equal that of height. For *A. ovalis*, shell depth is about 70% of shell height.

The relationship of whole weight and height in *A. ovalis* (Fig. 9c) is best described by the curvilinear equation: $W = aH^b$, where W = whole weight in grams, a = 0.0003, and b = 3.14 ($r^2 = 0.97$). As with *N. ponderosa*, the correlation ($M = 4E^{-05} H^{3.33}$) between height and wet meat weight (Fig. 9d) was more variable than with whole weight, and the coefficient of determination was slightly lower ($r^2 = 0.89$) than for the regression of height and whole weight. Mean whole weight for the *A. ovalis* sample was 34.2 g (± 21.2, n = 139), mean shell weight was 22.7 g (± 14.2,
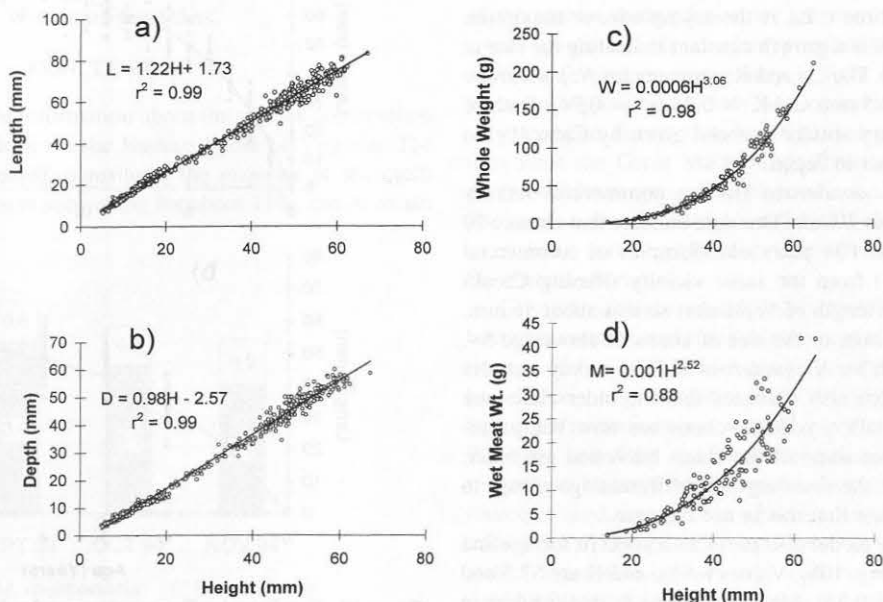

Figure 8. Regression of height versus length (a), depth (b), whole weight (c), and wet meat weight (d) for *N. ponderosa*. Data are from field surveys, commercial fisheries samples, and growth studies (*n* = 540 for a and b; *n* = 132 for c and d).
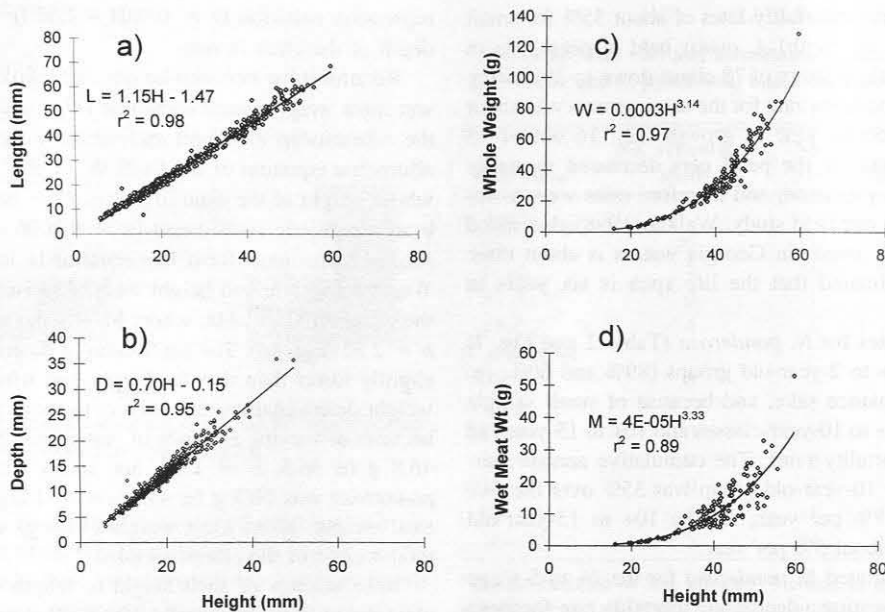
Figure 9. Regression of height versus length (a), depth (b), whole weight (c) and wet meat weight (d) for *A. ovalis*. Data are from field surveys, commercial fisheries samples, and growth studies (*n* = 778 for a; *n* = 641 for b; *n* = 139 for c and d).

$n = 139$), and mean wet meat weight was 11.5 g ($\pm$ 8.2, $n = 139$). Therefore, shell weight in *A. ovalis* constituted about 66% of total weight, and meat weight 34%, or an average of about 10% more meat weight for a given size than in *N. ponderosa*.

Age-size Relationships

We prepared acetate peels from clams taken in the field survey, augmented with clams purchased from fishermen. Some data from growth studies (1992 to 1994) were incorporated as baseline data points for 1- and 2-y-old *A. ovalis* and *N. ponderosa*. We fit age-length data to the Von Bertalanffy growth equation:

$$L_{(t)} = L_\infty (1 - e^{-kt})$$

where $L_{(t)}$ is length at time t; L_∞ is the asymptotic, or maximum theoretical length; and K is a growth constant indicating the rate at which L_∞ is approached. The L_∞ and K estimates for *N. ponderosa* (Fig. 10a) are: $L_\infty = 71.5$ mm and K = 0.24 ($r^2 = 0.94$). Both of these parameters are very similar to those given by Cahn (1951) for *A. granosa bisenensis* in Japan.

Mean length of *N. ponderosa* from a commercial fishery sample in 1992 was about 70 mm. Our data indicate that clams >70 mm in length would be 10+ years old. Samples of commercial catches (taken in 1994) from the same vicinity (Parting Creek) showed that the average length of *N. ponderosa* was about 56 mm, a decrease of about 14 mm, or the size of clams of about age 5+. In addition, mean length for *N. ponderosa* in field survey samples was about 54 mm, which also indicates that the older clams are being depleted, and smaller, younger clams are now being harvested. It is possible that some of the clams harvested are older, stunted clams; however, the size ranges for different age groups in the growth model suggest that this is not the case.

The Von Bertalanffy model also provides a good fit for age and size data for *A. ovalis* (Fig. 10b). Values for L_∞ and K are 57.5 and 0.45, respectively ($r^2 = 0.83$). Mean length for *A. ovalis* taken in the field survey was 27 mm, or about 1+ year-class clams, while mean length for *A. ovalis* in 1994 commercial fisheries samples

was 56.5 mm, or 5+ years old. We obtained only five *A. ovalis* over five years in age in survey samples, which suggests that this species does not live very long in this geographic area. This is also corroborated by the mortality data from articulated *A. ovalis* shells, and from laboratory observations where large *A. ovalis* held in water tables died as ambient water temperatures approached 27°C.

Commercial Fisheries Catch Data

Catch data from a commercial fisherman on the eastern shore (D. Bishop, unpubl.) showed that *M. mercenaria* constituted an
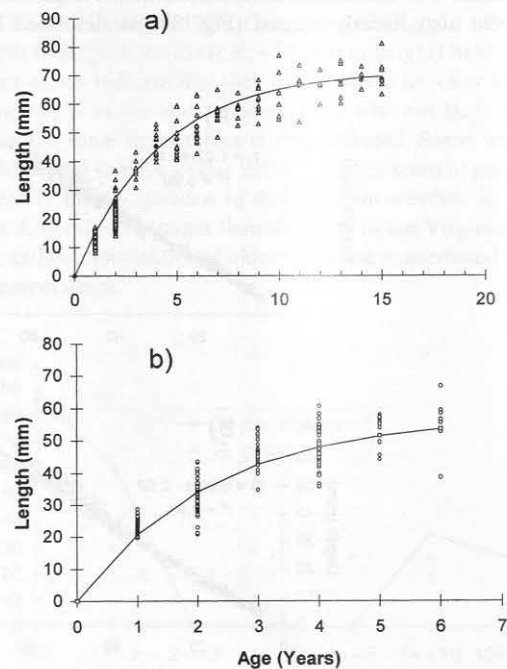

Figure 10. Von Bertalanffy growth curve for *N. ponderosa* (a), *n* = 379, and *A. ovalis* (b), *n* = 211, from the eastern shore of Virginia. See text for equations.

average of about 78% of his catch with mechanical tongs, and blood clams (*N. ponderosa* and *A. ovalis* combined) 22% for the period of September to November 1994. The percentages of blood clams in catches for those three months were about 18% for September, 21% for October, and 26% for November. The species distribution was similar to that from the field survey samples (i.e., about 72% *Mercenaria* and 28% blood clams). Average daily catches (Fig. 11) for September, October, and November, 1994 were 4,373, 3,873, and 3,642 clams per day, respectively.

The estimated average catch per unit effort (i.e., clams in one tonging effort, covering 1.12 m²) during two days of fishing was 9.72 (*n* = 540) and 3.6 clams (*n* = 720), respectively, for an overall mean of about 6 clams per tonging effort (*n* = 1,260). This equates to an average density of 5.4 clams m⁻² in the harvest area. The average heights of *A. ovalis* and *N. ponderosa* from subsamples of September to November catches were 34.0 mm and 44.7 mm, respectively (Figs. 12a and 12b). The mean height for *N. ponderosa* was less than that for the commercial fishery sample taken in 1992 (70 mm) and the Parting Creek sample (56.0 mm) taken in 1993. The decrease in average size may indicate that overfishing is occurring.

During December 1994 and January 1995, Mr. Bishop worked in an area just north of Wachapreague, VA (Gargatha Creek) and reported catching almost all *A. ovalis*, the highest percentage catch of that species of which we are aware. His observation is noteworthy because of the normally small percentage of *A. ovalis* in catches, and indicates that small, dense beds of *A. ovalis* exist in some isolated locations. The average height for *A. ovalis* from the January sample in Gargatha Creek was 40.2 mm (Fig. 12c). Most of the clams were in the 30–40 mm size range (= 33 to 44 mm in length), or >3+ years old. The absence of 0+ year-class *A. ovalis* in commercial fisheries samples may simply reflect the difficulty in seeing and collecting very small clams in the mud and debris which accompany catches, or it may also indicate low recruitment and/or high mortality rates. Another, more probable explanation is the fact that small *A. ovalis* are epiphytic. During our study, the easiest place to find 0+ year-class *A. ovalis* was enmeshed in bryozoan and hydrozoan colonies attached to commercial mollusc floats near Quinby or Wachapreague Inlets.

CONCLUSIONS

Survey data provide information about the species composition of the blood clam fishery on the Eastern Shore of Virginia. The hard clam, *M. mercenaria,* constitutes the majority of the catch (72%, with *N. ponderosa* accounting for about 17%, and *A. ovalis*
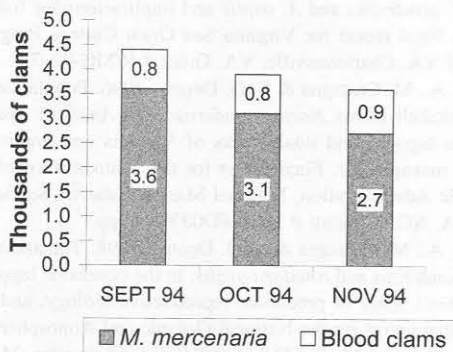
Figure 11. Average daily catch of blood and hard clams (*M. mercenaria*) by a fisherman on the eastern shore of Virginia (Sept.–Nov. 1994).
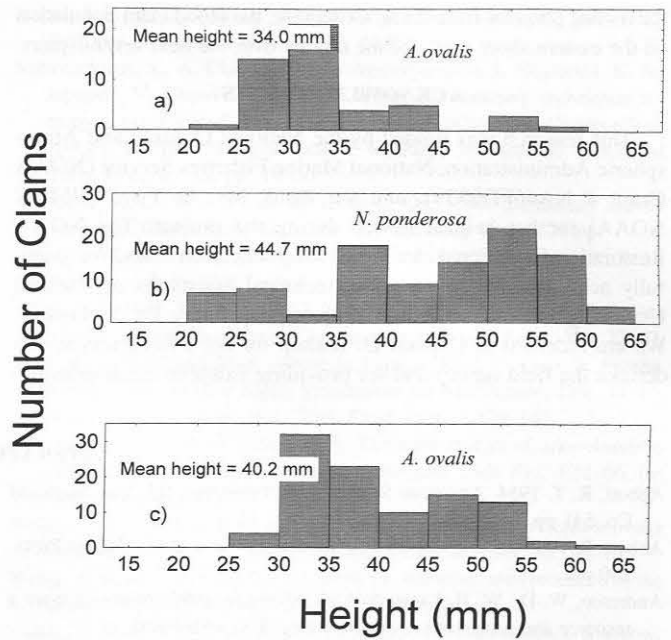
Figure 12. Height frequency distributions for *A. ovalis* (a) and (c) and *N. ponderosa* (b) from Quinby and Wachapreague, Virginia.

11%. However, age-length relationships clearly show that *N. ponderosa*, even though it is more abundant than *A. ovalis*, is a relatively slow-growing species, and may not be suitable for a commercial fishery with high exploitation rates. *Anadara ovalis* grows faster but appears to have a high mortality rate in most areas, as indicated by the relatively few, small ones that were taken in survey samples, the low percentage taken in commercial catches, and field experiments (McGraw et al. 1998).

We estimated abundance for *N. ponderosa* and *A. ovalis* to be about 16 million and 6.4 million clams, respectively, in the general area surveyed. Catch estimates range up to 1.5 million blood clams harvested annually in the survey area. Although this is about 15% of the estimated abundance, we are concerned that if fishing continues unabated, blood clam populations could be decimated within a few years, particularly in light of data showing that *N. ponderosa* grows so slowly and observations that settlement is very sporadic. Survey data as well as samples of commercial landings from the Great Machipongo River and other areas show a decrease in average size of *N. ponderosa*, indicating that *N. ponderosa* is currently being overfished and that there is a need to re-evaluate current policies governing the blood clam fishery on the eastern shore.

Given the distinct possibility of overfishing, we think one of the best conservation measures with regard to blood clams is the cultivation of *A. ovalis*. It has a comparatively fast growth rate, should be relatively easy to spawn under hatchery conditions, and could be grown in conjunction with *M. mercenaria* on existing leases. We have anecdotal evidence that natural set of blood clams is sporadic and undependable, but hatcheries could provide a reliable source of seed. In addition, effective, feasible methods of floating culture (i.e., "Taylor floats") are already in use for hard clams on the eastern shore (Luckenbach and Taylor); similar use for *A. ovalis* would substantially reduce predation and enhance survival rates. If *A. ovalis* can be successfully cultured, this may augment or supplant the harvest of blood clams by other means and, possibly, lessen some of

the fishing pressure from them. Otherwise, the blood clam population on the eastern shore may decline rapidly over the next several years.

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