2007 SOUTHEASTERN NATURALIST 6(3):413–434

Corbicula fluminea (Asian Clam) in the Roanoke River, North Carolina: A Stressed Population?

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Abstract - Principal component analysis, correlation, and multiple regression were used to evaluate the relationships of 12 environmental variables to the recorded values of density and biomass of *Corbicula fluminea* (Asian clam) collected in a 13-km segment of the lower Roanoke River delta, NC, in 1992–1993. Sediment fractions, pH, conductivity, and oxygen saturation accounted for the most variance in density, and, with the addition of shell length, water temperature, and river kilometer, accounted for the most variance in biomass. Similar variables were important in principal component analysis and multiple regression, although regression was less useful due to lower tissue weights of clams at two stations, which resulted in low predictive power for some regressions. The results of this preliminary census indicate that there were relationships among Asian clam density and biomass and various environmental factors. Higher density and biomass were found where the substrate was > 40% fine sand, < 45% silt, and < 8% organic content. This habitat type was limited in the study area and resulted in the majority of Asian clams living in a 4-km segment. Seasonal extremes in water temperature, low pH and calcium concentration, and phytoplankton limitations may also have contributed to the low weight of Asian clams in the Roanoke River. A more extensive sampling effort is warranted to further define the role of environmental stressors in the Asian clam population.

Introduction

Corbicula fluminea (Müller) (Asian clam) is a fast-growing species whose life-history strategy of short maturation and reproductive time (Kraemer and Galloway 1986), and whose hermaphroditic nature with multiple spawning events (McMahon 1991, McMahon and Williams 1986) allows populations to expand rapidly in new environments. This is particularly true in habitats that have been altered by human disturbance (Kat 1982). Disturbances can include dredging, sedimentation, introduction of pollutants, and alteration of the flow regime by dams or diversions. Disturbances have also resulted in the decline of native unionid mussels (Williams et al. 1993), leaving habitats open to colonization by introduced species such as Asian clams. Unionid mussels can compete with Asian clams in habitats that are not subjected to disturbance (Kat 1982). The Roanoke River basin in North Carolina has been altered by sedimentation arising from agriculture and construction (Mulligan et al. 1993), water-flow regulation by dams (Zincone and Rulifson 1991), and water discharges: 14 of 41 permitted discharges emptied directly into the river (Briggs 1991) during the study period. Only 15% of the evaluated stream distance (4031 km) supported

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fully the designated use of the water resource (Mulligan et al. 1993) at the time of the present study.

Asian clams (light morph of McMahon 1991, New World form A of Lee et al. 2005, voucher specimens placed in New York State Museum) were first reported from the Roanoke River and from the nearby Chowan River in 1978 (Kirby-Smith and Van Dover 1979, Lauritsen and Mozley 1983). Many North Carolina coastal rivers were invaded from 1978 to 1981 (Lauritsen 1986). Juvenile unionid mussels were abundant in the lower Roanoke River in 1978 (Kirby-Smith and Van Dover 1979), but adult unionid mussels were rare a few years later (Clarke 1983). Cooper and Rulifson (1993) reported collecting only two juvenile unionid mussels in the lower Roanoke River in 1992–1993. The decrease in unionid mussel abundance may be due to the combined influence of environmental stress and Asian clams.

The present study is based on data from Cooper and Rulifson (1993), and additional data collected at the same time but not reported. Subsequent analysis of these data indicated that tissue weights of Asian clams in the Roanoke River were less than those found in the Chowan River (Lauritsen and Mozley 1983), and Altamaha River, GA (Sickel 1979). The objectives of this study were to compare the density and distribution of Asian clams sampled in 1978 to that of 1992–1993, and to discern if there were any relationships between low tissue weights of Asian clams and specific environmental stressors. The potential stressors included sediment grain size, pH at the sediment-water interface, dissolved oxygen, conductivity, and water temperature, all of which were measured during the collection of Asian clams, as well as historical data on phytoplankton density.

Methods

Study site

The study site was a 13-km portion of the delta in the lower Roanoke River, comprised of three distributaries, including a portion of the Cashie River, which emptied into western Albemarle Sound (Fig. 1). Two permitted discharges were within the study site: 1) the Weyerhaeuser pulp and paper mill discharged untreated wastes (1960–1970) and biologically-treated wastes (1970–1987) into Welch Creek—the effluent was re-directed into the river through a diffuser pipe in 1988 that extended across the bottom of the river just upstream from stations R5 and R6; and 2) a sewage treatment plant serving the town of Plymouth (WWTP; Fig. 1) that directed effluent into the river between stations R10 and R16. River water flow was regulated by a series of dams in the upper watershed. The largest dam was at Roanoke Rapids, approximately 133 river kilometers (rkm) from the study site.

Twenty-one stations were selected within the lower Roanoke River and western Albemarle Sound. Stations were designated by letter-number combinations to indicate their location: Roanoke River (R), Middle River (M), Cashie River (C), and Albemarle Sound (S). Stations were paired except for station M121. Station pairs R1 through R10 were selected as comparisons to a benthic survey done in 1978 (Kirby-Smith and Van Dover 1979); the remaining stations were chosen to provide continuity with stations used in *Morone saxatilis* Walbaum (striped bass) studies (Rulifson et al. 1992). One station of each pair was at less than 3-m depth (odd-numbered stations), and the other was at a depth greater than 3 m (even-numbered stations) except at stations

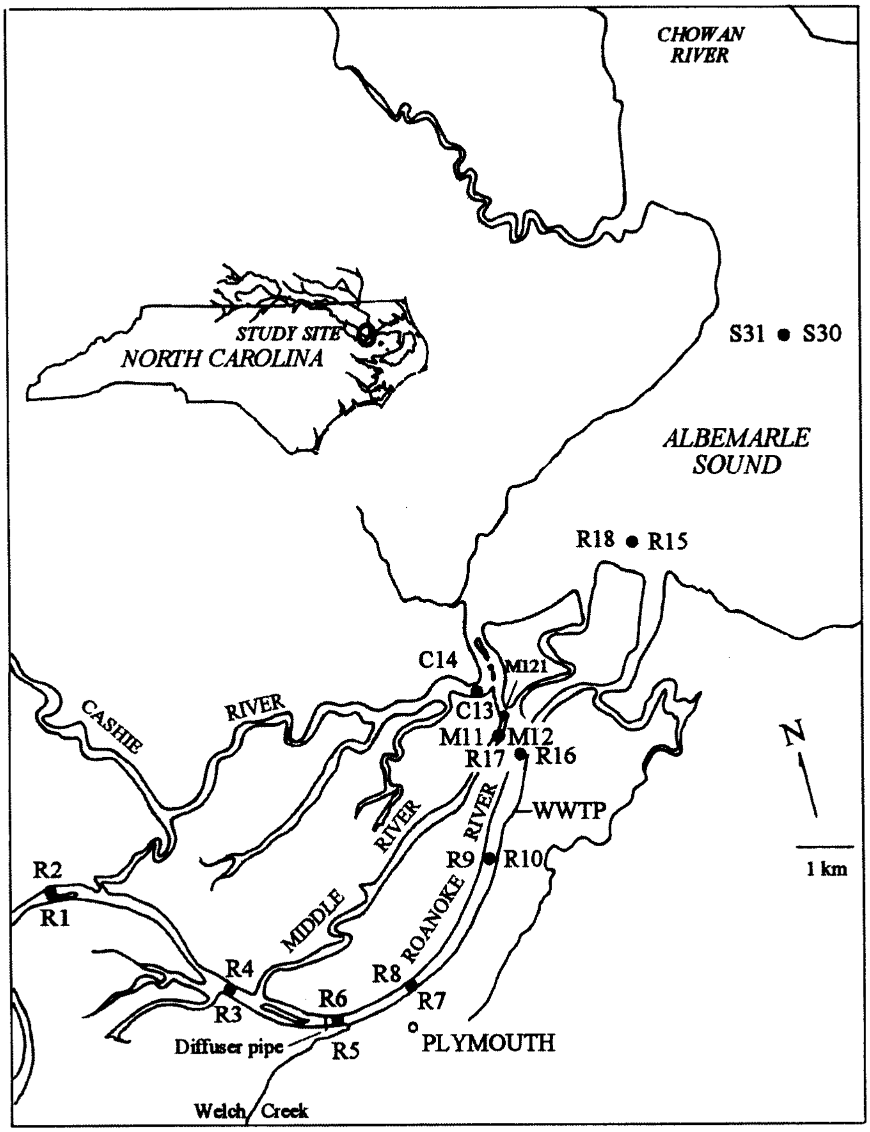


Figure 1. Study area of the lower Roanoke River and western Albemarle Sound, NC. Inset map of North Carolina shows the drainage basins for the Roanoke and Chowan rivers. Diffuser pipe is the paper-plant outflow, and WWTP is the outflow of the waste-water treatment plant for the town of Plymouth.

S15 and S18 where water depth was equal at 3 m. Station M121 was the deepest part (maximum of 21 m) of the lower Roanoke River and was selected to evaluate the potential effects of greater depth on the Asian clam population. Asian clams from station M121 were compared to those collected at stations M11 and M12.

Sampling

One 120-ml sediment subsample was taken from each of six ponar grabs at each station to estimate grain size (3 samples) and organic content (3 samples). Three samples were adequate to be within 90% of the mean for sediment fractions and organic content based on standard deviation (Department of Environment 1992). Samples were stored at 3 °C until the analyses were made. Sand, silt, and clay fractions were determined by the dispersal method (Folk 1980) and expressed as percentage of dry weight of the sample. Organic content was determined by loss on ignition and was expressed as a percentage of the dry weight (Wilde et al. 1972). Temperature and dissolved oxygen were measured at the water-sediment interface at each station once in each sample month, with the assumption that these measured values would be representative of the average for that month. Sediment pH (from ponar grabs) was measured using a Corning meter. A summary of the environmental variables is given in Table 1.

Clam density was determined from three replicate samples taken over an approximate 100-m^2 area at each station in September and November of 1992 and February, May, and July of 1993 using a 15-cm square (0.02-m^2) ponar dredge. Time and budget constraints limited the sampling effort to less than the 92 samples per station that would be required, based on sample standard deviation, for the estimate of density to be within 80% of the mean. However, the number of samples taken was adequate for an initial assessment of chronic effects in tissue weight or length frequency, and this collection method was similar to that used in those studies cited in comparisons. Shell erosion and tissue weights were determined from separate ponar collections of 20 live clams from the deeper-water stations (but not station C14 due to scarcity of clams). Some clam shells were found to be empty, so the number reported per station may be less than 20. Each sample was washed through a 0.5-mm mesh screen. Those clams used to estimate shell parameters and density were preserved with 10% buffered formalin, while those clams used to estimate dry weight and erosion were transported to the laboratory on ice and then processed. Dry tissue weight was measured to 0.01 mg, and the values used in regressions were transformed by cube root (CRDTW; Doherty et al. 1990). The parameters of shell length (SL) and shell height (SH) of clams > 10 mm were measured to 0.1 mm with a vernier caliper, and clams < 10 mm were measured to 0.01 mm using an ocular micrometer in a stereo-microscope. Clams were segregated by SL for analysis: > 15 mm = large, 1.6 to 15 mm = small, and < 1.6 mm = immature. Erosion was estimated by measuring the length and height of the eroded area on one valve and expressing the eroded area as a percentage of the total SL by SH area. This method would underestimate the extent of erosion in that it does not account for the depth of erosion.

Statistical analyses

All statistical tests were done using SAS (1988). The relationships among 12 environmental variables and density and biomass of Asian clams were examined with principal components analysis (PCA), correlation, and multiple regression. A decision level of $\alpha = 0.10$ was used for correlations due to variability of the data and a level of $\alpha = 0.05$ was used for other tests except for multiple comparisons where alpha was adjusted using the Bonferroni correction. PCA was used to derive linear combinations of uncorrelated variables from a correlation matrix of the original environmental variables. The principal components (PC) would reduce the number of variables needed to account for most of the variance present in the original data. Data sets were segregated by sampling month to reduce influences from autocorrelation that is likely to be present in time-series data. The variables rkm, sampling depth, water temperature, conductivity, SL, SH, and pH at the water-sediment interface were transformed by logarithms (base 10) and the variables oxygen saturation, sand, silt, clay, and organic matter (all

Table 1. Abiotic and biotic variables used to characterize each station. The variables sampling depth (SD), bottom water temperature (BWT), oxygen saturation (OS), conductivity (C), sediment pH (pH), shell length (SL), and shell height (SH) are means from samples taken in September, November, February, May, and July. The percentage of sand, silt, clay, and organic matter (OM) are means from sampling in September. Values in percent were transformed by arcsine and the remainder was transformed by $\log_{10}$. Station river kilometer (RKM) was determined by designating station S30 as 1.0. NC = no large clams collected.

	RKM	SD (m)	BWT (°C)	OS (%)	C (μmhos/ cm)	pH	Sand (%)	Silt (%)	Clay (%)	OM (%)	SL (mm)	SH (mm)
R1	16.5	2.5	18.8	67.9	128	6.3	23.6	56.1	20.2	7.7	26.9	25.4
R2	16.5	9.5	18.9	67.4	130	6.5	42.1	37.3	20.5	5.9	26.5	23.1
R3	13.5	3.4	18.7	64.7	120	6.5	14.4	56.3	29.3	5.9	29.9	27.9
R4	13.5	5.5	18.4	66.9	120	6.6	67.8	21.1	11.1	7.1	27.2	24.1
R5	11.5	3.2	19.0	66.5	120	6.5	33.9	51.6	14.4	7.1	NC	NC
R6	11.5	6.5	18.6	65.6	120	6.6	23.2	50.0	26.8	6.4	31.6	28.3
R7	10.5	2.4	18.7	68.1	140	6.4	7.6	70.4	21.9	8.1	NC	NC
R8	10.5	5.8	18.6	64.5	180	6.6	46.3	34.0	19.7	5.4	27.4	24.4
R9	8.5	2.8	17.5	63.4	160	6.5	16.6	54.6	28.7	6.9	24.0	21.5
R10	8.5	5.7	17.5	63.7	150	6.3	48.4	34.8	16.8	7.3	28.1	25.3
R16	6.5	4.4	17.9	64.8	160	6.3	21.5	51.0	27.5	8.1	23.7	21.6
R17	6.5	2.5	17.9	65.1	170	6.3	9.5	63.4	27.1	7.0	29.9	27.5
M11	5.5	2.1	17.7	67.8	130	6.5	4.6	69.9	25.4	7.0	28.9	26.2
M12	5.5	4.7	17.6	66.8	130	6.6	7.6	61.6	30.7	9.9	27.9	24.8
M121	3.0	15.5	16.9	74.0	130	6.3	12.9	55.5	31.6	12.9	27.2	21.9
C13	3.5	2.2	17.9	74.3	120	6.3	2.6	66.6	30.7	6.7	34.5	31.0
C14	3.5	11.5	17.6	64.1	120	6.3	2.1	75.2	22.7	8.1	30.4	27.1
S15	2.5	2.9	17.8	74.8	330	6.1	21.6	63.5	14.9	12.8	31.3	26.5
S18	2.5	2.9	17.8	74.8	330	6.1	26.6	63.6	9.8	20.5	29.3	24.6
S30	1.0	3.4	17.9	80.1	410	6.5	6.1	73.0	20.9	7.6	30.6	27.6
S31	1.0	3.4	17.8	80.2	320	6.5	96.7	1.4	1.9	0.5	29.5	25.8

expressed as percentages) were transformed by arcsine to achieve normality in distributions (Steel and Torrie 1980). Sampling depth, water temperature, pH, and percent organic matter were the only variables that had non-normal distributions in at least one month; however, all variables were transformed. Multiple regression models were developed to predict Asian clam density and biomass from the environmental variables. Each variable was regressed against density and biomass and the residuals were examined for normality. Variables for each regression model were used only if they were not correlated significantly ($r > 0.40$, $P > 0.05$) to other variables in the model. Variables used in the model were also examined for colinearity and influence (Cook's D statistic).

Results

Water chemistry

Mean bottom-water temperature was 27 °C (SE = 0.06) in September, 14 °C (SE = 0.06) in November, 6 °C (SE = 0.05) in February, 18 °C (SE = 0.11) in May, and 27 °C (SE = 0.26) in July with less than 3 °C variation among stations and between the river and western sound within each month. No temperature stratification was found on the sampling dates. Dissolved oxygen saturation at the water-sediment interface ranged from 34.5% in September to 101.2% in February, and was always higher in the sound than in the river for the same sample period. Conductivity ranged from 120 to 180 μmhos in the river and between 320 and 410 μmhos in the western sound. Sediment pH was significantly greater (general linear model [GLM]: $F = 4.70$, $P = 0.04$) at R1 through R10 (mean = 6.48) than at the other stations (mean = 6.34; Table 1).

Sediment

Stations could be segregated into three groups based on the sediment fractions: R2, R8, and R10 comprised one group where silt and sand occurred at 30–50%; the second group was composed of R4 and S31 which had more than 68% sand; and the third group was the remaining 16 stations where silt was present at > 50% (Table 1). The mean organic content was greater at S18, and less at R2, R3, R8, and S31 than the remaining stations (Tukey critical value = 5.38, $P = 0.05$), which did not differ significantly from each other. The mean organic content of the remaining stations was 7%. There was no significant difference in mean organic content between the shallow and deep water stations (Kruskal-Wallis: $\chi^2 = 2.42$, $P = 0.12$).

Shell length, shell height, dry shell weight, and erosion

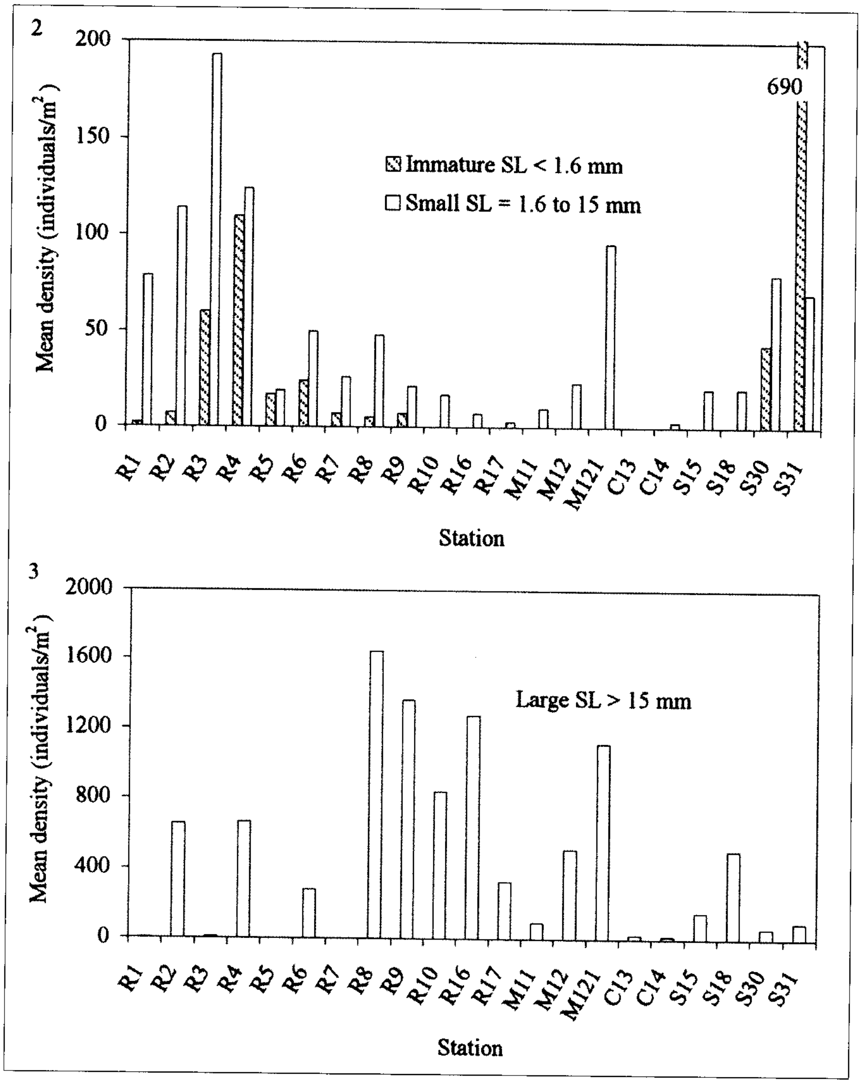
The relationship between SL and SH was best described by $SH = 0.8013(SL)^{1.03}$ for clams ranging in SL from 1.0 to 39.5 mm ($r^2 = 0.99$, $N = 4144$). The relationship of SL to dry shell weight (transformed by cube root; CRDSW) was described by $CRDSW = 0.099 + 0.055(SL)$ for clams with a SL of 20 mm and longer ($r^2 = 0.85$, $N = 906$). Clams from R6 and S30 were longer in SL and SH, and heavier in CRDSW than were clams at other stations, and clams from R16 were shorter in SL and SH, and lighter in CRDSW than clams at other stations (SL, SH: Tukey critical value = 4.978; CRDSW: Tukey critical value = 4.485, both at $P = 0.05$). Clams from M121 did not differ significantly in SL or SH from clams at M12, but were lighter in CRDSW.

All clams examined had some erosion (mean = 8.9%; SE = 6.7), which appeared to start with the umbo and progress anteriorly toward the valve edges. Many clams had discontinuous areas of erosion. The teeth and shell at the ligament were the primary structures with erosion damage (95% of clams), but only 20 clams (2.2%) were collected that had perforated valves. There were significant, but weak, correlations of erosion with the percent silt ($r = 0.12$, $P = 0.006$), pH ($r = -0.15$, $P = 0.004$), and oxygen saturation ($r = -0.16$, $P < 0.001$), but no significant correlation was found with the percent organic matter ($r = 0.05$, $P = 0.19$). The mean percent erosion was greater at M121 (Tukey critical value = 4.49, $P = 0.05$) than at other stations, and M121 contributed 90% of the clams with perforated shells. Clams from R2, R6, and R10 had significantly greater mean percent erosion than clams from the remaining stations, but did not differ significantly from each other. No significant correlations were found between mean percent erosion and SL, SH, or with CRDTW, perhaps due to the presence of erosion on all clams.

No significant differences were found in CRDSW among months. CRDSW was correlated significantly with SL ($r = 0.90$, $P < 0.001$) and SH ($r = 0.94$, $P < 0.001$) for all months combined suggesting that erosion did not affect the measurements of SL and SH. It is unlikely that erosion would affect SL values since erosion did not occur at the edges of the valves, but could have affected estimates of SH since erosion of the umbo would decrease the measured values of SH.

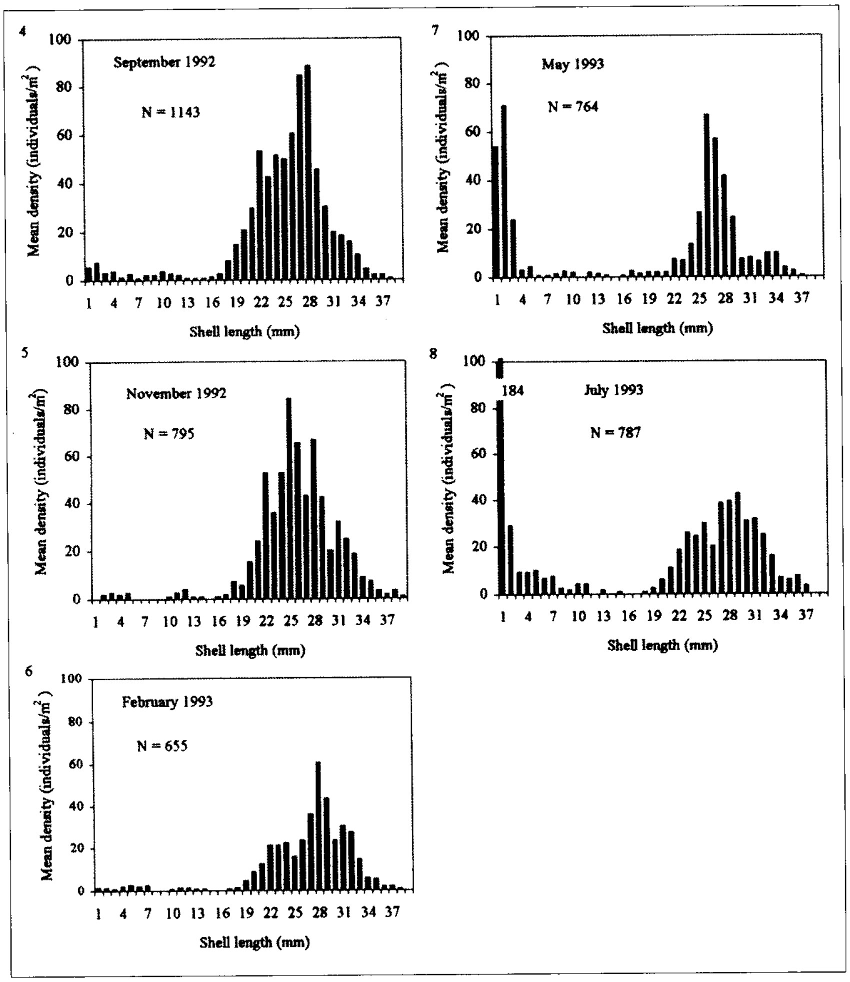
Density

Immature clam density was greater at R3, R4, S30, and S31 than at all other stations (Fig. 2). No immature clams were collected at river stations downriver from R9. The greater density of immature clams at S30 and S31 resulted entirely from the samples collected in July. Small-clam density was highest at R3 (Fig. 2) and was correlated significantly with density of immature clams ($r = 0.96$, $P < 0.001$), but neither immature- nor small-clam density was correlated significantly with large-clam density ($r = -0.18$, $P = 0.40$). Mean density of large clams varied as much as two orders of magnitude among months at most stations. Mean density was greater generally at stations downriver from R8 (Fig. 3), and R8, R9 and R10 contributed more than 40% of all clams collected in each month. No large clams were collected at R5 or R7. Mean density of large clams was greater (GLM: $F = 12.78$, $P = 0.006$) at stations deeper than 3 m than at stations at less than 3 m. Mean density of large clams declined by 40% from September to July (all stations combined), although the distribution of length frequencies remained similar (Figs. 4–8). Large-clam density was lower at those stations (R7, M11, C13, C14, S30) that had greater percentages of silt (except M12) but large-clam density was not correlated significantly with sediment fraction ($P > 0.16$). Density of small clams was low from September to February, but increased in May and July. Density of large and small clams was greater at M121 than at either M11 or M12. Immature clams were collected in each month except November, but were most abundant in May and July. Immature- and small-clam density was correlated significantly with percent sand in the sediment (small clams $r = 0.74$, immature clams $r = 0.73$, both at $P < 0.001$), and with percent organic content (both clam groups at $r = -0.49$, $P = 0.02$).



Figures 2 and 3. Extrapolated mean density (individuals/m²) by station of immature, small, and large Asian clams collected in the lower Roanoke River in 1992 and 1993.

PCA reduced the 12 environmental variables to 5 PCs that explained 87–92% of the variance in density in the original data over the five sample months. PC1 explained 31–37% of the variance in density by month and was characterized by greater loadings for sediment fractions in September, May, and July, and with greater loadings for water chemistry parameters in November and February (Table 2). PC1 was correlated with density in July (r = -0.75, P < 0.001) and was characterized by higher loadings for sand, silt, and clay (Table 2). PC2 explained 23–26% of the variance in density by month and was characterized by greater loadings for sediment fractions in September, November, and February, and with greater loadings for water chemistry and location in May and July. PC2



Figures 4–8. Extrapolated mean density (individuals/m^2) by SL of Asian clams (stations combined) collected in each month in the lower Roanoke River.

Table 2. Eigenvectors of five principal components for PCA analysis of abiotic and biotic variables related to Asian clam density, and the percentage of the variance explained by each principal component. The five principal components explained 88–92% of the variation within months. Values for each component range from -1.0 to +1.0 and those variables that are closer to |1.0| explain the most variation. The pcs with "*" were correlated significantly with density.

	September					November					February				
Variable	pc1	pc2	pc3*	pc4	pc5	pc1	pc2	pc3*	pc4	pc5	pc1	pc2	pc3*	pc4*	pc5
Rkm	-0.303	-0.37	0.168	-0.111	0.054	-0.406	-0.158	-0.009	0.128	-0.169	-0.43	0.146	0.066	0.159	0.139
Depth	-0.036	-0.207	-0.035	0.587	0.633	-0.041	-0.084	0.477	0.533	0.549	0.006	-0.026	0.453	0.589	-0.49
Temperature	0.336	0.139	-0.234	0.448	-0.113	-0.426	-0.072	0.139	0.142	-0.208	0.403	0.012	-0.181	0.019	-0.334
Saturation	0.342	-0.017	-0.326	0.301	-0.172	0.429	0.097	-0.167	-0.041	0.303	0.385	0.017	0.13	-0.38	-0.472
pH	0.044	-0.404	0.201	0.306	-0.396	-0.137	-0.326	0.153	-0.526	0.594	-0.286	-0.135	0.385	-0.331	0.089
Sand	0.354	-0.348	0.108	-0.153	0.258	0.137	-0.505	-0.113	0.249	-0.057	-0.102	-0.527	-0.047	0.207	-0.017
Silt	-0.356	0.37	-0.112	0.129	-0.183	-0.14	0.522	-0.107	-0.117	0.147	0.104	0.521	-0.104	-0.095	0.095
Clay	-0.369	0.117	0.224	0.418	-0.243	-0.302	0.335	0.215	-0.296	0.05	-0.03	0.469	0.319	-0.137	0.013
% organic	-0.205	0.379	-0.016	0.036	0.485	-0.003	0.443	-0.036	0.466	0.175	0.138	0.353	-0.219	0.538	0.14
SL	0.25	0.241	0.569	0.083	0.046	0.268	0.068	0.548	-0.076	-0.234	0.374	-0.076	0.407	0.086	0.359
SH	0.244	0.231	0.588	0.078	-0.006	0.253	0.052	0.559	-0.115	-0.259	0.365	-0.068	0.414	0.075	0.386
Conductivity	0.35	0.332	-0.153	-0.166	-0.01	0.428	0.068	-0.128	-0.02	-0.025	0.326	-0.233	-0.302	-0.006	0.302
% variance explained	33	23	14	10	8	37	25	17	8	5	33	26	15	9	7

	May					July				
Variable	pc1	pc2	pc3	pc4	pc5	pc1*	pc2	pc3*	pc4	pc5
Rkm	-0.223	-0.346	-0.248	-0.353	-0.094	0.12	0.48	0.099	0.336	0.163
Depth	-0.048	-0.133	0.121	0.807	-0.456	0.035	0.194	0.244	-0.684	0.367
Temperature	0.076	-0.264	0.53	-0.063	0.107	-0.08	0.381	-0.153	0.493	0.173
Saturation	0.358	-0.108	0.124	0.261	0.552	-0.275	-0.313	-0.214	0.051	-0.196
pH	0.065	-0.318	-0.393	0.225	0.366	-0.157	0.379	0.021	-0.081	-0.472
Sand	0.427	-0.244	-0.019	-0.146	-0.327	-0.446	0.046	0.321	0.066	0.237
Silt	-0.409	0.258	0.144	0.025	0.333	0.434	-0.095	-0.355	0.079	-0.069
Clay	-0.419	0.087	-0.217	0.263	0.164	0.405	0.181	-0.189	-0.267	-0.265
% organic	-0.281	0.215	0.392	-0.092	-0.196	0.329	-0.17	-0.152	0.094	0.603
SL	0.224	0.44	-0.281	0.023	-0.1	0.296	-0.185	0.531	0.196	-0.141
SH	0.218	0.449	-0.276	0.02	-0.091	0.301	-0.174	0.532	0.178	-0.172
Conductivity	0.328	0.324	0.307	0.012	0.179	-0.199	-0.455	-0.088	0.074	0.045
% variance explained	32	24	17	9	8	31	26	14	9	7

was not correlated with density. PC3 was correlated with density in September (r = 0.44, P =0.04), November (r = 0.41, P = 0.06), February (r = 0.40, P = 0.07), and July (r = 0.43, P = 0.05), and PC4 was correlated with density in February (r = 0.38, P = 0.09). PC3 and PC4 explained between 9 and 17% of the variation in density and were characterized by SL, SH, silt, depth, and percent organic matter (Table 2). These results suggest that greater clam density occurred at those stations that had greater depth, greater SL, less organic content, and less silt. Four other PCs were correlated with density, but explained 5% or less of the variation: PC11 in September (r =-0.61, P = 0.003, < 1%), PC7 in February (r = 0.40, P = 0.07, 2%), PC6 in May (r = 0.65, P = 0.001, 5%), and PC9 in May (r = 0.38, P = 0.09, < 1%). These four PCs were characterized by higher loadings in percent organic content, temperature, and rkm.

The regression models for May and July explained a high proportion of the variance in Asian clam density (Table 3) and were described by the abiotic variables rkm, depth, temperature, pH, and silt, and the biotic variable SL. Two of these variables were correlated with density: rkm (r = 0.55, P = 0.01) and silt (r = -0.82, P < 0.001). The models for the other three months were not significant.

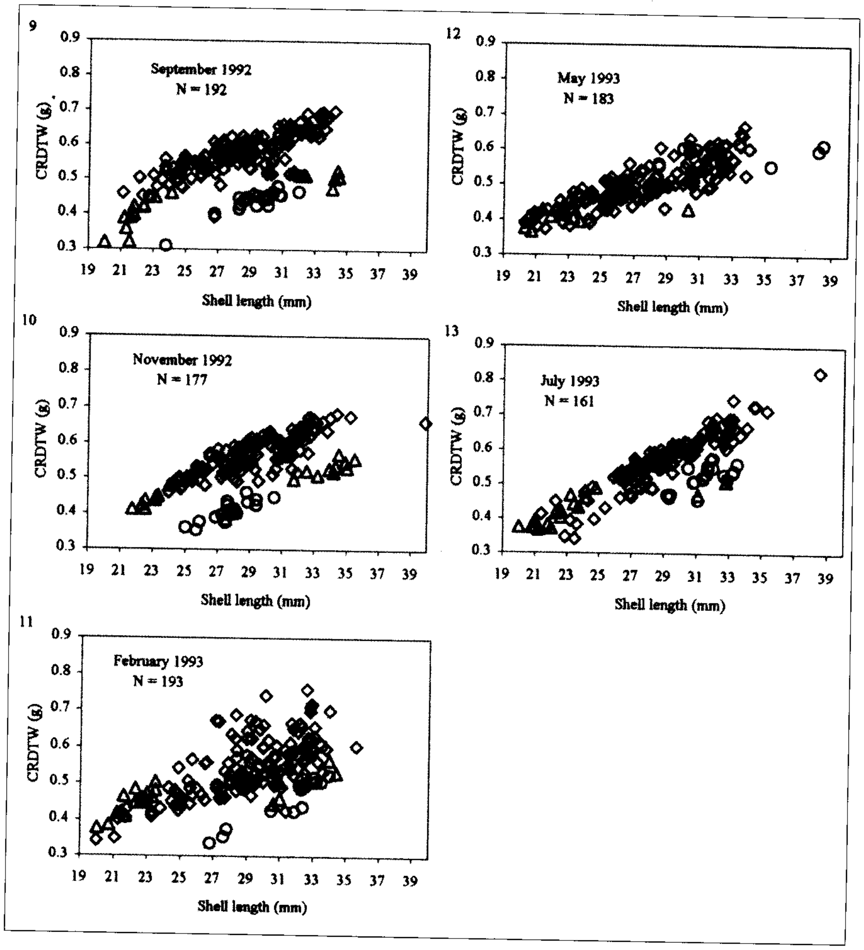
Dry tissue weight

The mean CRDTW of individual clams varied by month and by station. Mean CRDTW in September (0.551 g) was greater than that in November (0.534 g), February (0.523 g), and May (0.515 g), and CRDTW in May was less than that in September, November, and July (0.546 g; F = 13.74, P = 0.002). Linear regressions of CRDTW with SL in September, November, and February resulted in low predictive power for the regressions (r^2 ranged from 0.36 to 0.43) due to the lighter weight of clams from R16 and S18 (Tukey critical value = 4.48, P = 0.05) compared to clam weights from

Table 3. Multiple regression models to predict Asian clam density (D, individuals/m^2) in the lower Roanoke River delta. Significance values (P) are for the model and each coefficient. MSE = mean square error and N = number of stations on which the model is based.

	P				
Model	Coefficient	Model	R^2	MSE	N
May					
D = 453					
+945 (rkm)	0.002	< 0.001	0.79	81104	21
+818 (depth)	0.020				
+11904 (temperature)	0.017				
+22458 (pH)	0.04				
+33 (SL)	0.001				
July					
D = 729					
-63 (silt)	< 0.001	< 0.001	0.82	173832	21
-913 (rkm)	0.003				
-715 (depth)	0.061				

other stations. Plots of CRDTW with SL revealed that clams from R16 fell into two groups by SL: 1) clams at 20–24 mm ranged from 7% less weight in September, to similar weight in November, May, and July, and to 5% greater weight in February compared to clams from other stations; and 2) clams at 30 mm and longer were 20–30% less in weight in all months than were clams at other stations (Figs. 9 to 13). Clams from S18 were 20–25% less in CRDTW for a given SL than clams at other stations. A decline in mean CRDTW of clams at a SL of 30 mm or greater at most stations in May combined with an increase in CRDTW at S18 resulted in the regression CRDTW = 0.882 + 0.015SL ($r^2 = 0.71$). CRDTW increased at R4, R6, and R10, while CRDTW decreased at S18 in July and resulted in the regression CRDTW = -0.054 + 0.021SL ($r^2 = 0.72$).



Figures 9–13. Regression plots of CRDTW by month for Asian clams collected at deeper water stations. Triangles represent R16, circles represent S18, and diamonds represent all other stations. N = number of clams examined.

Biomass

Extrapolated values of Asian clam biomass ranged from a minimum of 1.96 g/m^2 (R6 in May) to a maximum of 357 g/m^2 (R8 in September), with most stations exhibiting wide fluctuations by month (SE ranged from 26.4 to 50.1). S30, S18, and M12 had less variation in biomass (SE ranged from 2.5 to 8.3). Mean biomass was similar in September (152 g/m^2) and November (156 g/m^2), declined by 35% in February to 99 g/m^2 and by 29% in May to 70.5 g/m^2, and then increased by 37% in July to 96 g/m^2. A biomass-to-density ratio was calculated to examine the influence that relative density had on the apparent biomass values. This ratio showed that the highest proportional biomass was at R6, which had relatively lower density (Fig. 14) but had clams that were heavier than those at other stations, and the least proportional biomass was at R16 and S18 due to the lesser weight of clams. There was a significant correlation between biomass and pH ($r = 0.46$, $P < 0.001$), and significant but weak correlations between biomass and rkm ($r = 0.31$), conductivity ($r = -0.29$), and shell erosion ($r = -0.29$; all at $P < 0.04$), indicating a trend of decreasing biomass with decreasing pH and increasing conductivity and shell erosion in a downriver direction.

PCA reduced the 12 original environmental variables to four principal components that explained 89% to 93% of the variance in biomass in the original data over the five sample months. PC1 explained 35% to 48% of the biomass variance within months (Table 4) and was best described by rkm, sand, silt, organic content, and conductivity. PC 1 was correlated significantly with biomass ($r = -0.68$, $P = 0.03$) in September and July ($r = 0.67$, $P = 0.03$; Figs. 15 and 16) and would suggest that greater biomass could be expected at those stations that were located upriver (greater rkm) with greater percent sand and lower conductivity.

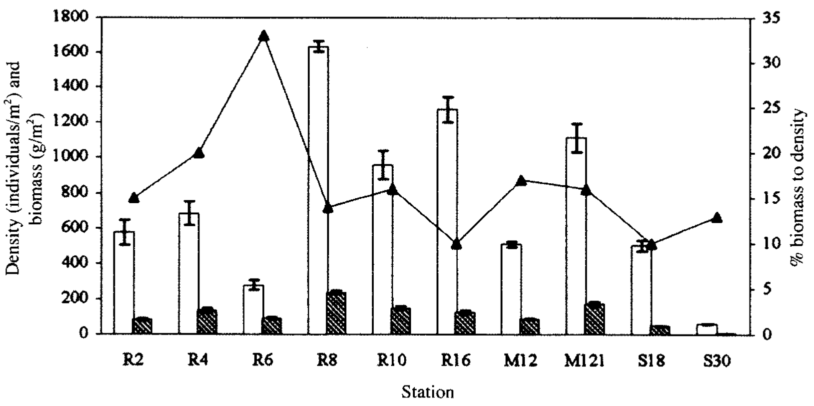


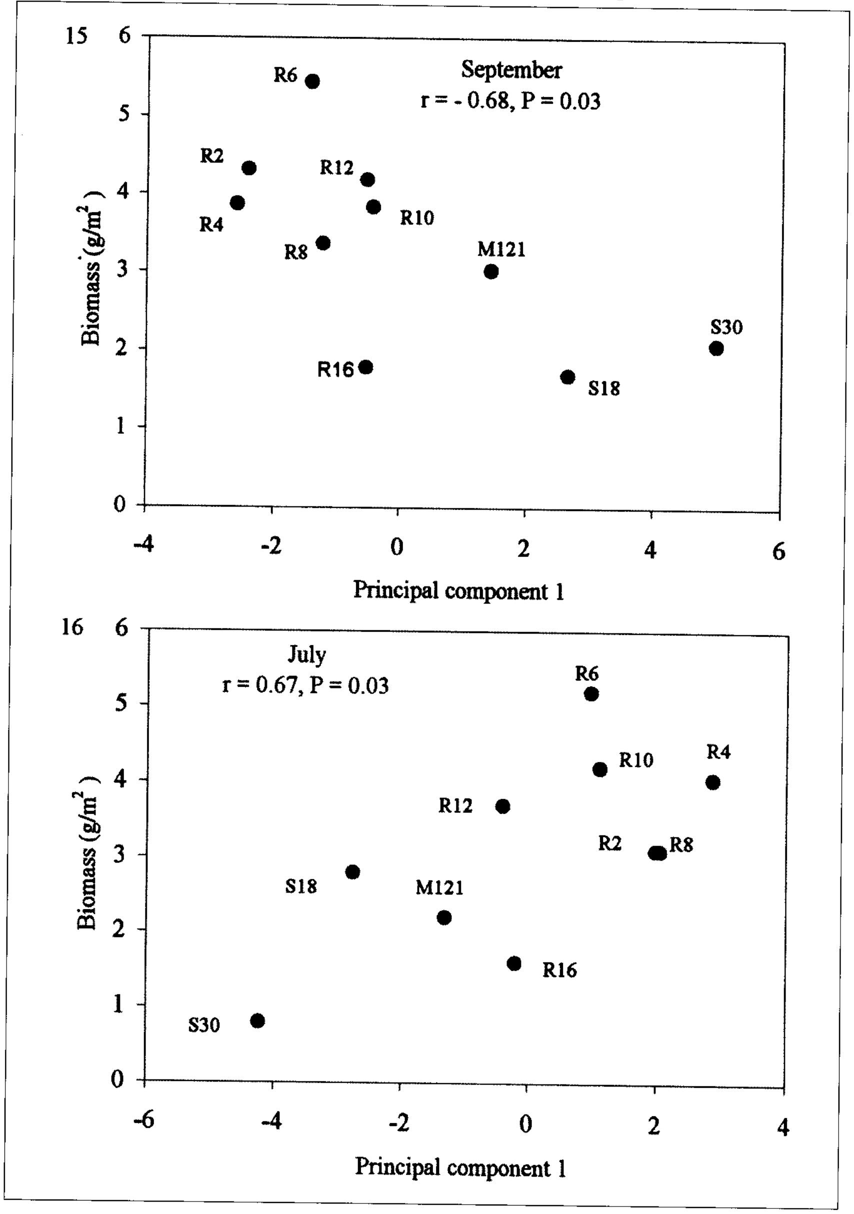
Figure 14. Extrapolated density (open bars, individuals/m^2), biomass (solid bars, g/m^2), and the biomass-to-density ratio (solid line) of Asian clams collected at deeper stations. Error bar represents one SE

Table 4. Eigenvectors of four principal components for PCA analysis of abiotic and biotic variables related to Asian clam biomass, and the percentage of the variance explained by each principal component. The four principal components explained 89–93% of the variation within months. Values for each component range from -1.0 to +1.0 and those variables that are closer to |1.0| explain the most variation. The pcs with "*" were correlated significantly with biomass.

	September				November				February			
Variable	pc1*	pc2	pc3	pc4	pc1	pc2	pc3	pc4	pc1	pc2	pc3	pc4
Rkm	-0.413	-0.049	0.003	0.046	-0.379	0.08	-0.146	-0.039	-0.391	-0.001	0.044	0.136
Depth	-0.15	0.472	0.016	0.503	-0.282	-0.145	0.256	0.628	-0.177	0.385	0.032	0.539
Temperature	0.34	0.287	0.169	0.118	-0.364	-0.09	0.231	-0.08	0.292	0.126	-0.457	0.042
Saturation	0.285	0.165	0.29	0.445	0.405	-0.013	0.001	0.15	0.318	0.345	-0.118	-0.189
pH	-0.207	-0.002	0.578	-0.19	-0.183	0.504	0.09	0.077	-0.234	0.188	0.324	-0.548
Sand	-0.354	-0.293	0.044	0.082	-0.27	-0.019	-0.507	0.096	-0.342	-0.332	-0.147	0.098
Silt	0.346	0.177	-0.063	-0.408	0.356	-0.004	0.33	-0.087	0.367	0.124	0.108	-0.095
Clay	-0.009	0.548	0.166	-0.375	-0.06	0.017	0.66	-0.14	0.064	0.594	0.203	0.095
% organic	0.224	-0.025	-0.557	0.024	0.275	-0.31	-0.064	0.556	0.274	-0.137	-0.31	0.328
SL	0.293	-0.288	0.18	0.387	0.175	0.513	-0.003	0.4	0.262	-0.177	0.476	0.295
SH	0.234	-0.319	0.42	-0.169	0.096	0.591	-0.033	0.022	0.228	-0.212	0.521	0.234
Conductivity	0.361	-0.249	-0.012	-0.066	0.358	-0.029	-0.211	-0.252	0.316	-0.327	0.016	-0.275
% variance explained	47	21	14	9	48	22	18	4	47	19	16	9

	May				July			
Variable	pc1	pc2	pc3	pc4	pc1*	pc2	pc3	pc4
Rkm	-0.43	-0.181	0.027	-0.099	0.43	-0.012	-0.029	0.003
Depth	-0.161	0.431	0.091	-0.169	0.237	-0.316	-0.169	-0.503
Temperature	-0.005	0.345	-0.418	0.305	0.292	-0.056	0.44	-0.019
Saturation	0.058	0.132	0.163	0.71	-0.297	0.078	0.508	-0.108
pH	-0.274	-0.023	0.355	0.332	0.226	-0.22	0.344	0.487
Sand	-0.324	-0.336	-0.31	0.087	0.352	0.258	0.156	-0.29
Silt	0.415	0.251	0.15	-0.015	-0.411	-0.112	-0.057	0.179
Clay	-0.024	0.365	0.5	-0.23	-0.047	-0.462	-0.336	0.325
% organic	0.283	0.154	-0.428	-0.289	-0.269	0.199	-0.271	-0.345
SL	0.285	-0.388	0.227	-0.078	0.145	0.485	-0.21	0.268
SH	0.296	-0.388	0.219	-0.069	0.152	0.473	-0.224	0.29
Conductivity	0.427	-0.102	-0.109	0.315	-0.349	0.223	0.302	0.012
% variance explained	35	23	17	14	42	25	14	10

None of the regressions produced significant models and thus failed to determine which variables were important for biomass. The variables used in the regressions may not have been sensitive to changes in biomass.



Figures 15–16. Relationship between principal component 1 (PC1) and biomass for September and July. PC1 was correlated significantly with biomass and suggests that greater biomass could be expected at those stations that were located at greater rkm with greater percent sand and lower conductivity.

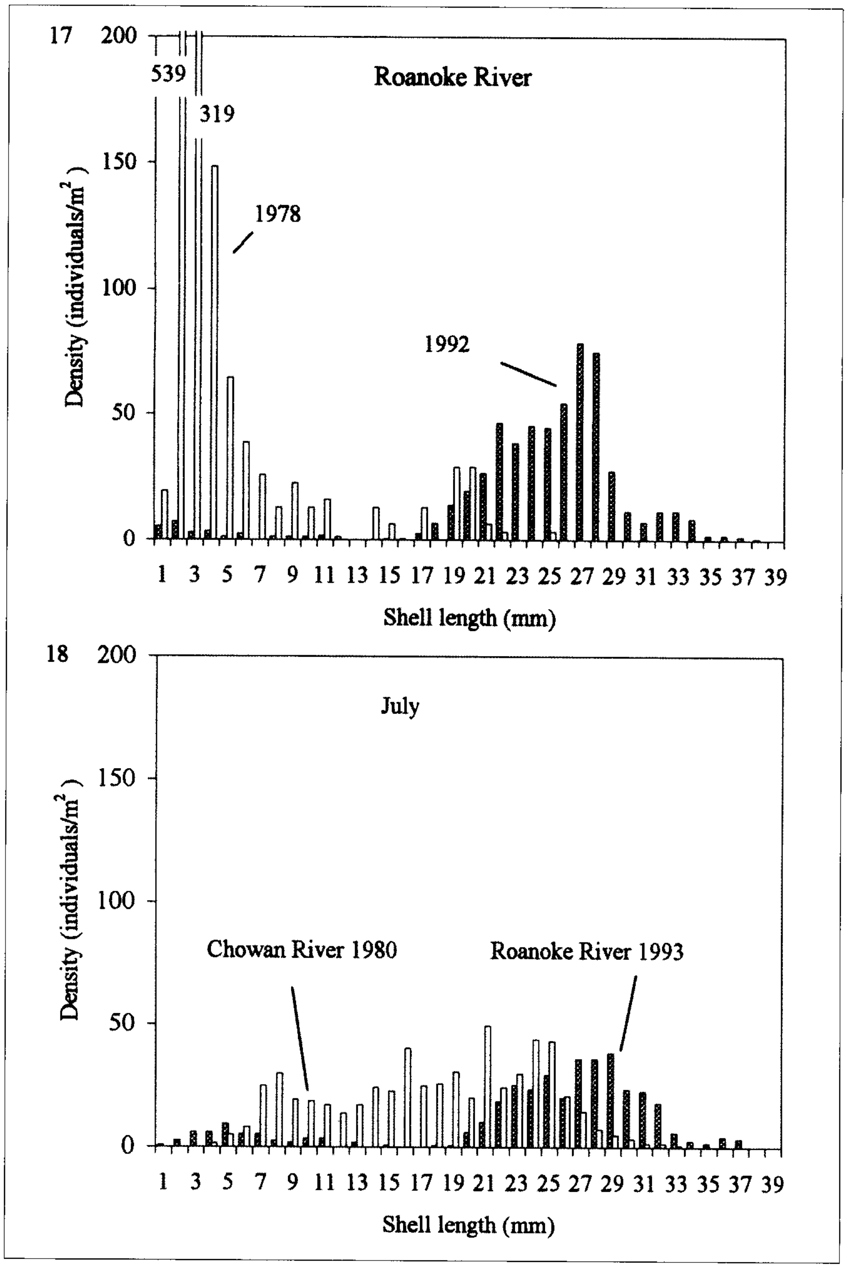
Discussion

The length-frequency distribution of Asian clams shifted from a population dominated by small clams (< 11mm SL) in 1978 to a population dominated by large clams (22–29 mm SL) in 1992 (Fig. 17), and both distributions exhibited a lower abundance of clams at 12–17 mm SL. The length-frequency distribution in the Chowan River was more uniform (Fig. 18) and did not exhibit a low abundance at any SL, although the sampling methods did not retain clams at less than 4 mm SL. Survival of juvenile clams is generally low in most populations, and mortality remains high in adult life (McMahon 1991), resulting in a population composed primarily of small clams. This was not true in the Roanoke River, where the population was dominated by large clams with a lower representation of small clams. It would seem that those clams that survive in the Roanoke River are able to reach a relatively large shell length, but without a corresponding increase in tissue weight. Joy (1985) and Doherty et al. (1990) found that gains in tissue weight were not always linear with shell growth.

Mean density of Asian clams shifted from greater abundance upriver of the paper-plant effluent in 1978 (Kirby-Smith and Van Dover 1979) to greater density downriver of the effluent in 1992–1993. Density increased at all stations common to both studies (R4 through R8, R10, and R16), except at R5, where density decreased. Lauritsen and Mozley (1983) reported greater densities of Asian clams downriver of a paper-plant effluent in the Chowan River and suggested that the effluent may have had a beneficial effect on Asian clam density by contributing suspended organic matter during the winter. Density was greater at many stations downriver of the paper-plant effluent in the Roanoke River in 1992–1993, but it is not clear if this was due to a beneficial effect of the effluent. R5, R6, and R7 had much lower density even though they were in close proximity to the effluent, and density at M121 was relatively high, but would not be influenced by the effluent. Organic matter from the effluent may have contributed to the greater tissue weight in clams at R6, which was highest in February.

Belanger (1991) reported reduced growth in SL and total body weight of Asian clams downriver of a WWTP in the Vermilion River, LA, due to low dissolved oxygen and chronic toxicity of the effluent. Asian clams at R16 had less tissue weight and SL compared to other stations; however, SL at R17 was greater than that at many upriver stations. The WWTP effluent generally flows down the east side of the river, and any effect may not impact R17 as much as at R16. There was no evidence of low DO in the present study, but the toxicity of the effluent was not tested.

Extrapolated values of Asian clam mean density increased from 69 individuals/m^2 in 1978 (Kirby-Smith and Van Dover 1979) to 649 individuals/m^2 in 1992–1993 at stations common to both studies, and coincided with a decrease in unionid mussels and *Rangia cuneata* (G.B. Sowerby I) (Atlantic rangia). Unionid mussels declined from 4.5 individuals/m^2 in the main river in 1978 to 0.8 individuals/m^2 in 1992–1993, and *Rangia* was reduced



Figures 17–18. Extrapolated mean density (individuals/m^2) of Asian clams by SL collected in September of 1978 (Kirby-Smith and Van Dover 1979) and 1992 from the Roanoke River; and from July of 1980 from the Chowan River (Lauritsen and Mozley 1983), and in 1993 from the Roanoke River. Collection methods used in the Chowan River did not retain clams < 4 mm SL.

from 8.0 to 1.2 individuals/m^2. *Rangia* was collected upriver to R4 in 1978, but only upriver to R10 in 1992–1993. Other studies have cited circumstantial evidence of declines in unionid mussels as an example of the competitive advantage of Asian clams, but Kat (1982) has added that it may also show that Asian clams have the advantage in colonizing habitats that have been degraded. The conditions estimated by the environmental stressors in the Roanoke River would seem to favor Asian clams over unionid mussels and *Rangia*, which may be indicative of a degraded habitat.

Many studies have used the presence of Asian clams at less than 1 mm SL as evidence of spawning (Doherty et al. 1990, Stites et al. 1995), and based on this criterion, spawning in the Roanoke River occurred primarily at R3 and R6 in May and in Albemarle Sound at S30 and S31 in July. Limited spawning occurred in September and February. The lack of immature clams in the main river downriver from R9 and in Middle and Cashie rivers would suggest that spawning does not occur in this part of the delta and that recruitment of small clams in the lower river comes from upriver, perhaps by the clams traveling downstream using mucous threads as sails (Prezant and Chalermwat 1984).

A comparison of dry weight of clams of similar SL from four southeastern rivers (Fig. 19) shows that clams sampled in the Roanoke River in 1993

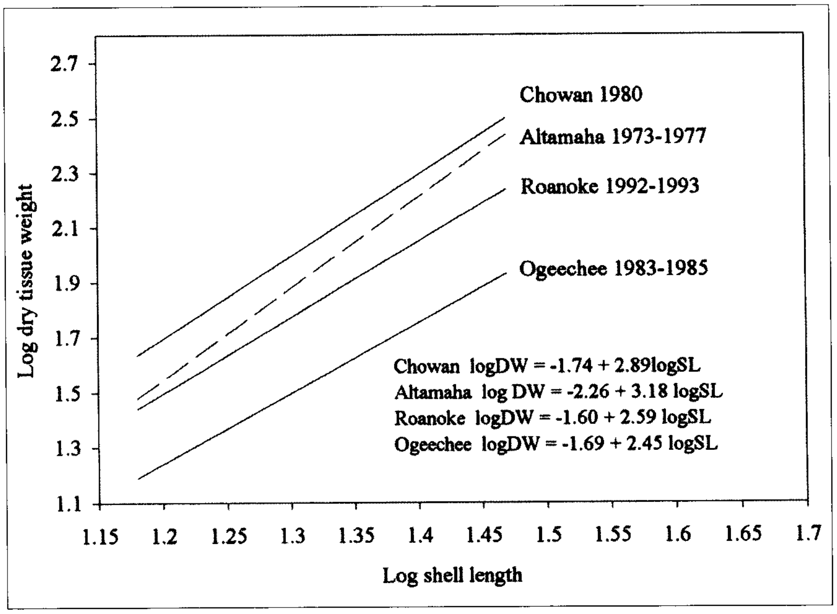


Figure 19. Relationships of log dry weight to log SL of Asian clams from four southeastern rivers. Chowan River data is from Lauritsen and Mozley (1983); Altamaha River data is from Sickel (1979); and data for the Ogeechee River is from Stites et al. (1995). Roanoke River data is from September and November, 1992, and February, May, and July, 1993.

achieved a mean dry weight that was 3–12% less than clams in the Chowan (in 1980) or Altamaha (in 1973–77) rivers but 16–21% greater weight than clams in the Ogeechee River (1983–85). The Ogeechee River habitat was considered by Stites et al. (1995) to be a stressful environment for Asian clams due to seasonal extremes in water temperature, low pH and calcium concentration, and food limitations. These variables may also be contributing stressors in the Roanoke River. The best tissue growth in Asian clams has been reported at 18–25 °C (Stites et al. 1995) so tissue growth could have been reduced in the Roanoke River when the mean water temperature was 27 °C in September and July. No growth has been reported at water temperatures of less than 10 °C (Joy 1985), which occurred in February (6 °C) in the Roanoke River. Mean calcium concentration was estimated to be 6 mg/L in the Roanoke River from 1988 to 1991 (Rulifson et al. 1992), lower than the 10 mg/L reported as stressful in the Ogeechee River. The discharge of acidic blackwater from the adjacent swamp forests (Riggs et al. 1993) may reduce the sediment pH, which could lead to shell erosion, such as was found on all Asian clams in the Roanoke River. However, shell erosion could not be shown to be a direct source of mortality in the Roanoke River. Compensation for shell dissolution is retarded in Asian clams since their shells lack the conchiolin layers that are present in unionid clams, and erosion was found to be an indirect source of mortality in Florida (Kat 1982). The mean chlorophyll-a concentration was 5.5 μg/l in the Roanoke River from mid-April to mid-June (1984–1991; Rulifson et al. 1992), which was less than a third of the mean concentration at which clams were food-limited in California (Foe and Knight 1985; 15.6 μg/l in spring, 18.9 μg/l in summer). An inverse relationship was found between the concentration of phytoplankton and river flows (Rulifson et al. 1992), which may result in periods of extreme food limitations, particularly in the spring when river flows are greater.

Competition for space because of high density (up to 2500 individuals/m^2) may also be a contributor to the lighter tissue weight of clams in the Roanoke River. Extrapolated values of mean density of Asian clams in the Roanoke River (542 individuals/m^2) was similar to that in the Altamaha River (522 individuals/m^2), but greater than that in the Chowan (200 individuals/m^2) or Ogeechee (< 200 individuals/m^2) rivers. The low estimated weights of clams from the Roanoke River collected in 1992 prompted another sampling in September 2000 at R8 to compare the weights of more recent clams to those collected at R8 in 1992. The CRDTW of the more recent clams was lighter than that found in 1992 ($N = 40$, $P = 0.007$) but with heavier CRDSW ($N = 40$, $P = < 0.001$). The untransformed dry shell weight of clams at 20 mm SL in the Roanoke was about 40% less than similar-sized clams in the Mud River, WV (Joy and McCoy 1975), but became more similar as shell length increased. The results of the present study would suggest that Asian clams are stressed in the Roanoke River, but not to the extent seen in the Ogeechee River. The low tissue weight but large shell size indicates that the population may have reached the carrying capacity of the river. More extensive sampling is warranted to confirm the status of this population of Asian clams.

Asian clam biomass in the Roanoke River ranged greatly by station and by month with a seasonal trend of decreasing biomass from winter to spring with a slight increase in summer. The winter-to-spring decrease may be attributed to mortality, although sampling periods were too far apart to document mortality. The extrapolated value of mean biomass (115 g/m^2) was greater than the maximum values in the Altamaha (31 g/m^2), Chowan (22 g/m^2), and Ogeechee (7 g/m^2) rivers. The difference can be attributed to sampling a larger proportion of large clams (> 20 mm SL) in the Roanoke River compared to the 10–20-mm SL range sampled in the other rivers.

Sediment fractions, pH, conductivity, and oxygen saturation accounted for the most variance in density, and, with the addition of shell length, water temperature, and rkm, accounted for the most variance in biomass. Similar variables were important in the regression models for density. Substrate characteristics were also important in the determination of biomass, but the variables SL and SH were not. The average substrate fractions of those stations that had higher density and biomass of large clams was more than 40% fine sand, less than 45% silt, and less than 8% organic content. These results agree with those of Belanger et al. (1985) who stated that adult clams prefer fine sand with low (< 8%) organic matter. The fine-sand fraction was less than 26% (by weight) on average in the lower Roanoke River; thus, not all areas of the lower river have a favorable habitat for large clams. Significant positive correlations were found between the percentage of sand and immature- and small-clam density, and significant negative correlations were found with immature- and small-clam density to the percentage of silt, clay, and organic content. The relationship of sand to clam size was similar to that found by Sickel and Burbank (1974) in that juvenile clams preferred coarse sand. The relationship of sand to clam size in the Roanoke River was not universal as no immature clams and less than 15% of the small clams were collected downriver from R10 even though the substrate at six of these stations contained medium-coarse to coarse sand. Higher percentages of silt and organic matter at many of these stations, as well as lower pH, may have reduced the suitability of the habitat. Immature and small clams were collected in the Western Sound (S30 and S31), where sand was the dominant substrate fraction with less silt and organic matter. The most favorable environment for Asian clams appears to depend upon clam size: upriver of R4 for immature and small clams, and at R6, R8, R9, and R10 for large clams. A more extensive sampling effort is needed to confirm these relationships.

Acknowledgments

This research was supported, in part, by Weyerhaeuser Corporation, and the Wilford A. Dence Memorial Fellowship from the State University of New York at Syracuse. I would also like to acknowledge the assistance of Dr. Brian Underwood (SUNY-ESF), Deborah Daniel (East Carolina University), and Dr. Robert Herrmann

(Weyerhaeuser Corporation). Dr. Cliff Siegfried (New York State Museum) verified the identity of a voucher series of clams.

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