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Effect of Connecticut Yankee Power Plant on Population Dynamics of Asiatic Clams and Their Interactions with Native Bivalves

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Abstract.—The Asiatic clam (also known as Asian clam) *Corbicula fluminea*, first reported in the Connecticut River in 1990, was the dominant bivalve around Connecticut Yankee nuclear power station (CY) during the 10-year period (1991–2000) of this study. This population extended its range upriver at least 22 km from 1991 to 1992. *Corbicula* winter survival was positively correlated with winter water temperatures and negatively correlated with spring freshet river flows. For example, no *Corbicula* were found following the two coldest winters of the study (1993–1994 and 1995–1996). Regardless of the level observed for winter population survival, study sites were repopulated each year by August, attributed to passive downstream movement from populations in refugia from winter stresses (e.g., upstream thermal discharges at Middletown and South Meadow power stations, or groundwater seeps). Small clams (2-mm size-class) dominated the CY thermal discharge canal during power plant operation because, by June of each year, discharge temperatures (>35°C) exceeded the upper thermal tolerance for this clam. The CY discharge, therefore, was not an important winter refuge. In years following CY closure (1997–2000), a year-round *Corbicula* population was established in the discharge canal, but abundance at river sites around CY remained similar to levels observed during power plant operation. Our findings suggest that *Corbicula* has established a permanent population in the Connecticut River with little impact on native bivalves up to the last year of this study in 2000.

Introduction

The Asiatic clam (also known as Asian clam) *Corbicula fluminea* is a freshwater clam, native to Southeast Asia, now common in Europe, Africa, the Pacific Islands, and North and South America (McMahon 1982; Counts 1986). In its native range, *C. fluminea* (termed *Corbicula* throughout this report) is a commercial species collected and cultured for human consumption (Chen 1990; Phelps 1993). Once introduced to North America, this clam spread rapidly because of its high reproductive capacity, adult brooding of young to a free-living juvenile stage, fast growth, early maturity, effectiveness of all stages of development to readily disperse by water currents, and tolerance to a wide range of environmental stresses (Gardner et al. 1976; Eng 1979; Sickel 1979, 1986; McMahon 1983). Its ability to clog industrial water systems makes *Corbicula* a very costly problem for water-dependent industries (Isom 1986; McMahon and Lutey 1988). By fouling water systems at electric generating stations, particularly nuclear power stations, *Corbicula* causes significant safety problems as well (Ingram 1959; Goss and Cain 1975; McMahon 1977; Goss et al. 1979; Mattice 1979; USNRC 1981; Johnson et al. 1986; Page et al. 1986).

Corbicula were initially identified at Connecticut Yankee nuclear power station (CY), which is located on the lower Connecticut River (Figure 1), during a cleaning of the service water system in April 1990 (Morgan et al. 1992, 2003). The discovery of *Corbicula* at CY necessitated the development of an effective control methodology. *Corbicula* is highly resistant to short-term application of conventional biocides because of its ability to tightly close its valves during treat-

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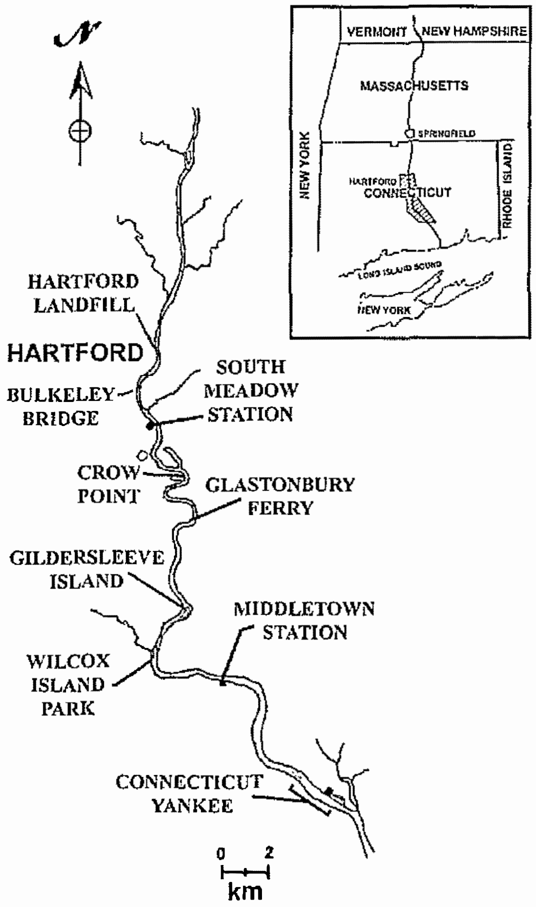

FIGURE 1. *Corbicula fluminea* sampling sites used in surveys conducted in November 1991 and 1992 to determine the extent of up-river clam abundance.

ment (Mattice et al. 1982; Neitzel et al. 1984; Page et al. 1986). However, continuous chlorination is effective in controlling *Corbicula* (Isom 1971; Goss and Cain 1975; Cherry et al. 1986). The continuous low level (<0.1 ppm, Total Residual Chlorine) chlorination of the service water system at CY was approved by the Connecticut Department of Environmental Protection (CTDEP) and began in April 1991. As a condition of the permit, CTDEP required CY to initiate a monitoring study of the *Corbicula* population in the lower Connecticut River. This paper summarizes the results of studies from 1991 to 2000, including data for *Corbicula* distribution, growth, fecundity, and abundance. In addition, native clam and mussel abundance data are presented and examined for possible interactions with *Corbicula.*

Methods

Surveys of the distribution of Connecticut River *Corbicula* population were conducted in November of 1991 and 1992. In 1991, sampling began at CY and continued upriver at intervals of 3–10 km (Middletown station, Wilcox Island Park, Gildersleeve Island, Glastonbury Ferry, Crow Point, and South Meadow station; Figure 1). In 1992, sampling was extended upriver to the Bulkeley Bridge and Hartford Landfill area. In these surveys, sediments were screened using a 3.4 mm, U.S.A. Standard Testing Sieve, which retained clams larger than approximately 6 mm in shell length. All sampling sites were located in the tidal freshwater areas of the Connecticut River.

Corbicula abundance, growth, reproduction and recruitment were studied at five sites in the vicinity of CY from August 1991 to November 2000. Four sampling sites were located in the mainstem river (Figure 2): Haddam Island (A); vicinity of CY intakes (B); down-river of CY intakes (C); and in the vicinity of the CY discharge canal outfall (D). A fifth site was located at the head of the CY discharge canal (E). Water depth at sampling sites ranged from 1 to 6 m at mean low water.

Sampling began in August 1991 and continued annually in May, August, and November through November 2000. Sampling at site D did not start until August 1993. Five 0.1-m^2 bottom samples were obtained at each site using a

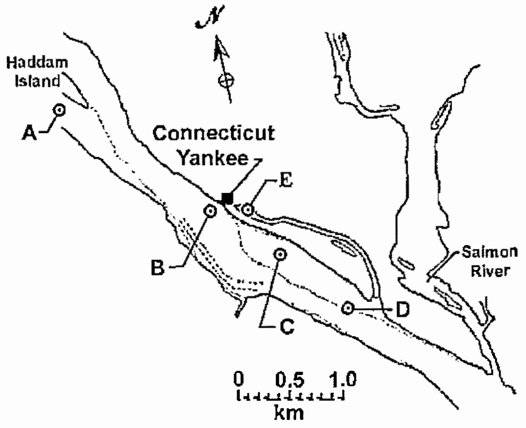

FIGURE 2. Location of the sampling sites (A–E) in the vicinity of CY.

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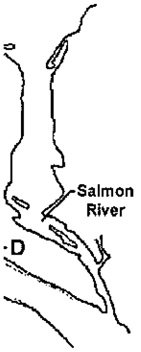

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weighted Peterson Grab. Sample processing techniques were similar to those of Gardner et al. (1976). Grab samples were sieved in the field by passing the sample through a series of three screens (6.3-, 2.0-, and 1.0-mm mesh sizes). Clams and sediment retained on the 1-mm screen were subsampled in the field by placing a well-mixed 1-L sample in an elutriator (Magdych 1981) for 3 min at a water flow of 20–30 L/min. The overflow from the elutriator was collected on a 1.0-mm mesh sieve and sorted in the laboratory under a dissecting microscope (10×). Sediment and clams retained on the 6.3- and 2.0-mm screens were taken to the laboratory and washed through a series of five U.S.A. Standard Testing Sieves (19.0-, 12.5-, 6.3-, 3.4-, and 2.0-mm mesh sizes). Size-classes were based on the sieve size in which clams were retained. Clams retained on the 1.0-mm sieve averaged 2.0 mm in shell length; on the 2.0-mm sieve, 4.1 mm; on the 3.4-mm sieve, 6.7 mm; on the 6.3-mm sieve, 14.1 mm; on the 12.5-mm sieve, 19.3 mm; and on the 19-mm sieve, 31.1 mm. The calculated densities (clams/m^2) are used in this study as a measure of abundance. Native bivalve species collected during the processing of these sediment samples were reported only at the total abundance level. Winter survival of clams was defined as the ratio of May clam abundance to November abundance from the previous year, expressed as a percentage.

Several hundred adult clams (>8.0 mm in shell length) were collected from river sites in June 1991 and in May 1992–1994 and held in two lantern-nets, one in the river and the other in the CY discharge canal. Clam growth was monitored monthly from 1991 to 1994 by measuring shell lengths of 12 randomly selected clams from these nets. Each year, monthly measurements were made until total winter mortality occurred in the river (December–February) or summer mortality occurred in the discharge canal (usually June).

Clam fecundity was monitored monthly using techniques of Aldridge and McMahon (1978). Fecundity was assessed on the 12 clams selected for growth estimates in each month that living clams could be found. Each clam was brought to the laboratory and held under static conditions at 20°C for 24 h in a 100-mL beaker filled with filtered Connecticut River water. The number of juveniles released during this period was recorded and used as an index of spawning activity. Additional fecundity assessments were made by dissecting these clams and noting the presence of brood progeny. Maturity of gametes was assessed by removing egg and sperm cells from the gonadal tissues and examining the cells under a compound microscope (400×).

To estimate *Corbicula* recruitment to bottom sediments in the Connecticut River and CY discharge canal, plastic trays (34.5 × 47.0 × 12.5 cm, inside dimensions) were filled with defaunated marine beach sand (<1 mm in grain size). Two sets of four sediment trays were enclosed within wooden frames (84 cm × 112 cm, outside dimensions) partitioned into four compartments (37.0 cm wide × 48.0 cm long × 14.0 cm high) and anchored to the bottom near the mouth of the discharge canal on 30 May 1991 and in the Connecticut River just upriver of the CY intakes (site B) on 6 June 1991. At each site, four trays were placed in each frame; two trays were covered with 6.4 × 6.4 mm plastic mesh screening, and two were not covered. The screen-covered trays were stocked with 50 adult clams (>8 mm), and the uncovered trays were left barren. One replicate tray for each treatment (screen-covered and uncovered) was collected and screened for *Corbicula* during river surveys in August and November 1991. Nearly all clams were dead in May 1992 and sampling was terminated.

Connecticut River flow rates were obtained from the USGS Thompsonville CT monitoring station (USGS 2002). Water temperature was recorded every 15 min at the CY intake and discharge using the Northeast Utilities Environmental Data Acquisition Network. Statistical analyses were performed using SAS version 8 software (SAS Inc., Cary, North Carolina). Abundance data in tables are presented using arithmetic means. Statistical testing (SAS General Linear Models Procedure) of abundance data were performed after log transformation. *T*-tests were performed on log-transformed abundance data, and depending on the results for the equality of variances test, either a pooled or Satterthwaite method was used to determine degrees of freedom. The relationships between winter clam survival and temperature or flow indices were tested using the rank-order Spearman correlation statistic. Growth and reproduction data were not transformed prior to analysis and are presented as arithmetic means.

Results

River Water Flow and Temperature

Annual Connecticut River water flow averaged 509 m^3/s over the 10-year period from 1991 to 2000. Mean monthly flow rates peaked during April in 8 of 10 years with the average April flow rate ranging from a low of 422 m^3/s in 1995 to a high of 2,099 m^3/s in 1993 (Figure 3). Similarly, maximal flow rates for daily averages usually occurred in April and often exceeded 1,700 m^3/s. These values, which were collected at the Thompsonville Connecticut gaging station, represent flows beyond any tidal effects. Semidiurnal tides affect river flow rates and bring an average 425 m^3/s of additional flow to the lower Connecticut River in the vicinity of CY (Merriman and Thorpe 2004 [1976], this volume), causing periodic fluctuations in river height of ~1 m (NSI 1995; Rozsa 2001). Tidal influences are large in relation to natural flow during periods of low river discharge and are absent or nearly absent during freshet conditions (Rozsa 2001; Boyd 2004 [1976], this volume). Daily average ambient water temperatures ranged between −1.7°C and 30.6°C during the 10-year study period (Figure 4). Discharge water temperatures at CY during plant operation were 8–12°C above ambient river temperatures. The maximum discharge flow of 25 m^3/s was directed through a man-made canal 1 km long before mixing with the ambient Connecticut River waters.

Distribution

In November 1991, *Corbicula* was observed as far north in the Connecticut River as Gildersleeve Island, where density averaged 168/m^2 (Figure 1; Table 1). Gildersleeve Island is approximately 16 km upstream of CY, where density averaged 531/m^2. Between these sites, clam densities were 150/m^2 at Middletown station and 12/m^2 at Wilcox Island Park. In November 1992, clams were documented 22 km further north at South Meadow station (30/m^2), which is just south of Hartford,

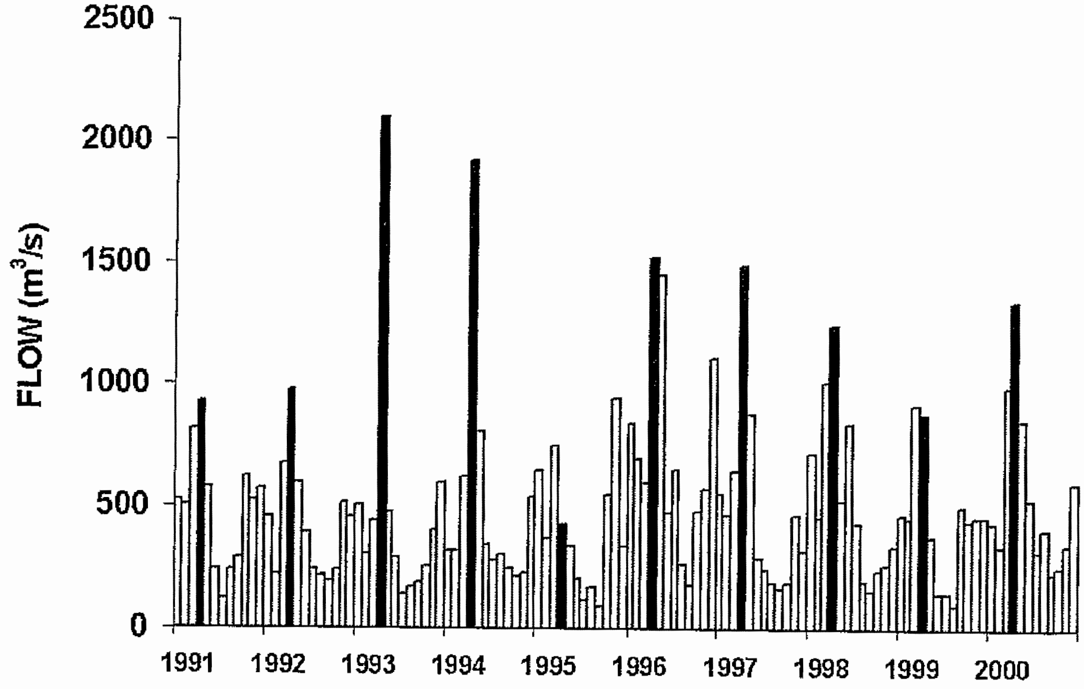

FIGURE 3. Monthly mean flow of the Connecticut River as measured at the Thompsonville station from January 1991 through December 2000. Black bars are April mean flows.

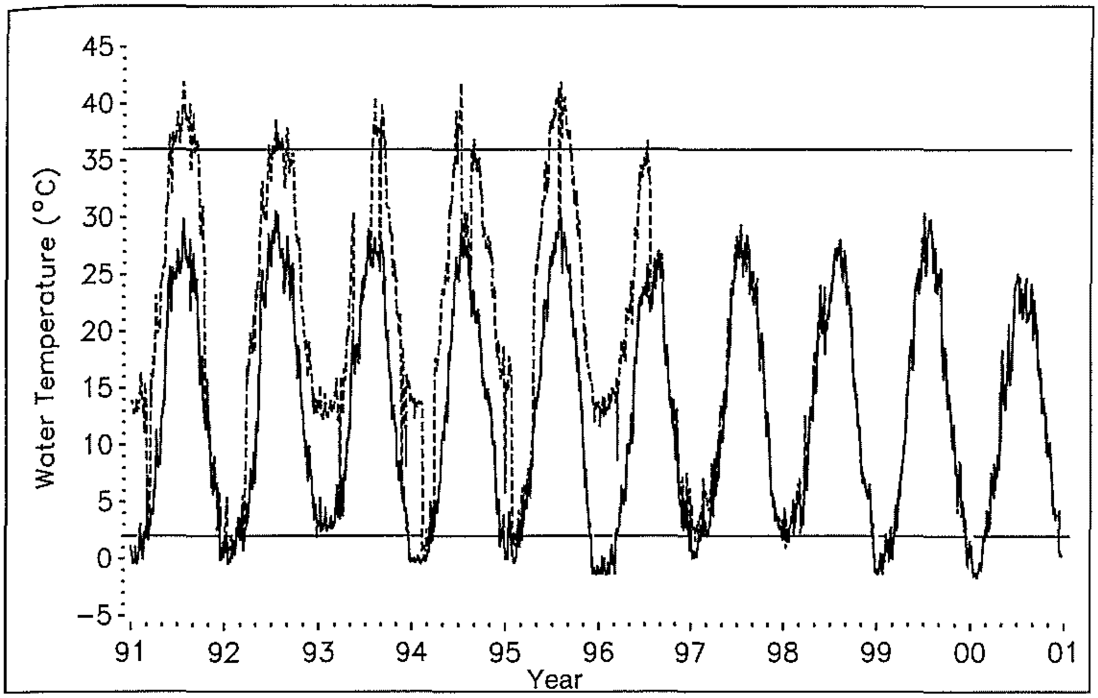

FIGURE 4. Intake (——) and discharge (----) water temperatures at CY from 1 January 1991 to 1 January 2001. Horizontal reference lines represent upper and lower lethal temperature limits for *Corbicula fluminea*. CY shut down in July 1996, as revealed by discharge temperatures tracking intake temperatures.

Connecticut. Clam densities were higher in 1992 than in 1991 at all sites, from 28/m^2 at Crow Point, approximately 3 km downstream of South Meadow station, to 9,169/m^2 at Middletown station.

TABLE 1. Mean abundance of *Corbicula fluminea* during the November 1991 and 1992 Connecticut River surveys.

	Abundance[a]	
Location	1991 clams/m^2	1992 clams/m^2
Connecticut Yankee (CY)	531	2,182
Middletown station	150	9,169
Wilcox Island Park	12	–[b]
Gildersleeve Island	168	3,300
Glastonbury Ferry	0	–
Crow Point	0	28
South Meadow station	0	30
Bulkeley Bridge	–	0
Hartford landfill	–	0

[a] Abundance estimates for clams > 5.6 mm in shell length (3.4-mm screen).

[b] Site was not sampled.

Abundance

Mean annual total abundance of *Corbicula* at CY sites from 1991 to 2000 was highly variable with significantly ($P < 0.05$) higher abundance in 1992, 1995, and 1999 than any other year of the study, ranging from 1,158/m^2 in 1995 to 2,610/m^2 in 1992 (Table 2). Annual abundance in 1998 and 2000 was 326 and 286/m^2, respectively. These abundances were significantly lower ($P < 0.05$) than those in 1992, 1995 and 1999, but significantly higher ($P < 0.05$) than those in 1993, 1994, 1996, and 1997, which ranged from 45/m^2 in 1996 to 138/m^2 in 1997.

Seasonal abundance (i.e., abundance in May, August, and November collections) was also highly variable (Table 2). May abundance was consistently the lowest value observed during the year; 10-year averages for May abundance ranged from 24/m^2 at site B to 86/m^2 at site A. Averages for all sites combined show November abundance was highest in 8 of 10 years. November abundance was lowest at site D (365/m^2) and highest at site A (2,299/m^2).

TABLE 2. Mean total abundance (clams/m^2 ± 95% CI) of *Corbicula fluminea* at each sampling site near the Connecticut Yankee power plant in the Connecticut River from August 1991 to November 2000.

Site Month	Year 1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	All years
A											
May	–	124 ± 115	12 ± 33	0	202 ± 161	0	10 ± 21	104 ± 147	146 ± 44	174 ± 284	86 ± 36
Aug.	640 ± 290	5,552 ± 3,980	8 ± 10	54 ± 59	3,052 ± 2,369	44 ± 52	118 ± 120	630 ± 440	4,076 ± 1,500	650 ± 477	1,482 ± 633
Nov.	1,642 ± 724	11,158 ± 4,315	332 ± 347	576 ± 341	2,452 ± 1,768	60 ± 50	648 ± 373	1,498 ± 168	3,552 ± 2079	1,036 ± 238	2,299 ± 959
Average[a]	1,141	5,611	117	210	1,902	35	271	744	2,591	620	1,331
B											
May	–	20 ± 26	0	0	30 ± 37	0	10 ± 28	14 ± 19	86 ± 60	54 ± 41	24 ± 11
Aug.	288 ± 99	982 ± 346	18 ± 31	40 ± 49	1,574 ± 759	32 ± 28	38 ± 27	196 ± 54	1,626 ± 346	196 ± 46	499 ± 186
Nov.	272 ± 215	2,688 ± 659	138 ± 102	110 ± 97	1,874 ± 1,829	80 ± 147	204 ± 73	326 ± 129	1,604 ± 595	278 ± 295	757 ± 289
Average	280	1,230	52	50	1,159	37	84	179	1,105	176	441
C											
May	–	20 ± 26	0	0	164 ± 200	0	8 ± 22	26 ± 46	136 ± 114	26 ± 45	42 ± 25
Aug.	270 ± 208	1,170 ± 645	40 ± 37	84 ± 52	1,934 ± 1,216	100 ± 64	42 ± 34	260 ± 199	1,590 ± 742	376 ± 381	587 ± 220
Nov.	508 ± 180	1,780 ± 1,078	140 ± 64	84 ± 71	1,184 ± 576	34 ± 27	220 ± 350	330 ± 121	956 ± 213	144 ± 152	538 ± 181
Average	389	990	60	56	1,094	45	90	205	894	182	401
D											
May	–	–	–	0	98 ± 73	0	4 ± 111	8 ± 22	8 ± 16	58 ± 71	25 ± 16
Aug.	–	–	74 ± 110	94 ± 61	754 ± 283	48 ± 55	30 ± 23	78 ± 54	1,300 ± 447	242 ± 161	328 ± 147
Nov.	–	–	214 ± 306	130 ± 143	580 ± 339	146 ± 105	294 ± 252	442 ± 56	922 ± 166	192 ± 116	365 ± 96
Average	–	–	144	75	477	65	109	176	743	164	249
All sites[b]											
May	–	55 ± 40	4 ± 9	0	124 ± 56	0	8 ± 8	38 ± 33	94 ± 35	78 ± 58	45 ± 13
Aug.	399 ± 132	2,568 ± 1,548	35 ± 24	68 ± 22	1,828 ± 624	56 ± 22	57 ± 28	291 ± 130	2,148 ± 619	366 ± 139	745 ± 192
Nov.	807 ± 390	5,209 ± 2,647	206 ± 91	225 ± 119	1,522 ± 567	80 ± 38	350 ± 137	649 ± 273	1,758 ± 637	412 ± 189	1,023 ± 284
Average	603	2,610	89	98	1,158	45	138	326	1,334	286	625

[a] Annual averages (clams/m^2) pooling the May, August, and November samples.

[b] Average abundance of clams, pooling the four sites.

Examination of *Corbicula* population structure from 1991 to 2000 shows juvenile clams (2- and 4-mm size-classes) significantly more abundant ($P < 0.05$) than first-year adults (7- and 14-mm size-classes) or clams older than 1 year of age (19- and 31-mm size-classes, Tables 3, 4, and 5). The overall annual average for older size-classes was only 6/m^2 as compared to 282 and 336/m^2 for first-year adult and juvenile size-classes, respectively.

Abundance was also highly variable from site to site (Table 2). Mean abundance at site A (1,331/m^2) was significantly higher than at other river sites. Average annual abundances (clams/m^2) at sites B (441), C (401), and D (249) were not significantly ($P < 0.05$) different from one another. Spatially, mean annual abundance decreased from site A (the northernmost site) to site D, which was the closest to the CY discharge canal. Mean annual abundance of *Corbicula* within the CY discharge canal (Site E) was substantially less than that at river sites and ranged from 25/m^2 in 1993–4,091/m^2 in 1992 (Table 6). Seasonally within the discharge canal, May abundance (0–92/m^2) was significantly ($P <$ 0.05) lower than August (0–12,174/m^2) and November (24–880/m^2); November abundance was usually higher than in August.

Mean *Corbicula* abundance for all river sites combined was not significantly different ($P >$ 0.05) between CY operational (1991–1996) and postoperational (1997–2000) periods. Similarly, the difference between total *Corbicula* abundance in the discharge canal during operational and postoperational years was not significant ($P > 0.05$). However, abundance in the discarge canal for ≥7 mm size-class clams was significantly higher ($P < 0.05$) in August and November samples during the postoperational period versus the operational period.

Recruitment

Uncovered trays placed in the river without *Corbicula* in June 1991 were colonized by 72 clams (444/m^2) in August and by 133 clams (820/m^2) in November. Size of recruited clams in August ranged from 1.5 to 17.2 mm with a mean shell length of 6.8 mm, and 1.5–22.3 mm in November with a mean shell length of 9.4 mm. Screen-covered trays seeded with 50 adult-size clams/tray (14.1-mm average size) collected upstream of CY sites had 587 clams (3,620/m^2) in August and 1,511 (9,318/m^2) in November. In these trays, clams in August ranged from 1.5 to 19.3 mm with a mean shell length of 7.8, and in November, the size range was 1.5–22.6 mm with a mean shell length of 11.4 mm. In May 1992, 2 live and 145 dead (shell only) clams were recovered from both uncovered trays. In the screened trays, 1,877 clams (all dead) were recovered.

Survival

Average survival of *Corbicula* in the river from November to May for 1992–2000 was 9.9% at site A, 9.3% at site B, 10.4% at site C, and 12.7% at site D (Table 7). Overall winter survival of *Corbicula* (all river sites combined) was positively correlated with average winter water temperature (December–April; $r_s = 0.87$, $P = 0.004$) and negatively correlated with the April flow index ($r_s = -0.91$, $P = 0.002$; Table 8). In addition, winter survival was also negatively correlated to the number of days that water temperatures averaged less than or equal to 1°C ($r_s = -0.73$, $P = 0.04$). *Corbicula* winter survival was not significantly correlated with the number of days that water temperature was less than or equal to 2°C ($r_s = -0.65$, $P = 0.08$).

However, spatial differences among sites were evident between environmental stress indices and winter survival. At site A, the site furthest from the CY, all four indices were significantly correlated with *Corbicula* winter survival: average winter water temperatures ($r_s = 0.92$, $P = 0.001$), peak flows in April ($r_s = -0.74$, $P = 0.036$), the number of days that were less than or equal to 1°C ($r_s = -0.87$, $P = 0.004$) and less than or equal to 2°C ($r_s = -0.82$, $P = 0.013$). At the B site near the plant intakes, winter survival was significantly correlated with average winter water temperature ($r_s = 0.73$, $P = 0.04$) and peak flows in April ($r_s = -0.77$, $P = 0.02$). At C, only average winter water temperature ($r_s = 0.85$, $P = 0.02$) was significantly correlated with survival. At D, the closest site in the river to the CY discharge, winter survival was not significantly correlated with any of the four indices. *T*-tests comparing percentage winter survival during operational and postoperational years showed no differences at any of the four river sites.

Reproduction

Clams within lantern-nets in the Connecticut River showed the presence of eggs and sperm in

Average 603 2,610 89 98 1,158 45 138 326 1,334 286 625

[a] Annual averages (clams/m^2) pooling the May, August, and November samples.

[b] Average abundance of clams, pooling the four sites.

TABLE 3. Mean total abundance (clams/m² ± 95% CI) of *Corbicula fluminea* in the 2- to 4-mm shell-length size-classes at each sampling site near the Connecticut Yankee power plant in the Connecticut River from August 1991 to November 2000.

Site	Year										All
Month	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	years
A											
May	–	10 ± 18	12 ± 33	0	176 ± 150	0	8 ± 22	104 ± 147	102 ± 51	6 ± 11	46 ± 24
Aug.	302 ± 236	4,246 ± 3,060	0 ± 0	18 ± 25	1,883 ± 1,937	44 ± 52	72 ± 88	488 ± 449	1,998 ± 547	352 ± 312	940 ± 447
Nov.	520 ± 313	5,924 ± 2,463	232 ± 265	456 ± 328	758 ±1,040	38 ± 37	506 ± 305	710 ± 467	1,228 ± 1,241	292 ± 174	1,066 ± 513
Average[a]	411	3,393	81	158	939	27	195	434	1,109	217	706
B											
May	–	4 ± 11	0	0	28 ± 33	0	10 ± 28	12 ± 20	80 ± 59	26 ± 35	18 ± 10
Aug.	170 ± 52	768 ± 302	0	16 ± 44	866 ± 733	14 ± 14	16 ± 19	156 ± 76	1,104 ± 322	24 ± 31	323 ± 127
Nov.	186 ± 123	2,162 ± 710	100 ± 90	82 ± 67	854 ± 1,149	64 ± 150	152 ± 82	222 ± 118	680 ± 419	74 ± 64	457 ± 202
Average	178	978	33	33	583	26	59	130	621	75	275
C											
May	–	4 ± 11	0	0	156 ± 197	0	6 ± 17	26 ± 46	114 ± 105	14 ± 32	36 ± 24
Aug.	116 ± 123	914 ± 599	18 ± 38	22 ± 20	996 ± 851	88 ± 59	12 ± 27	184 ± 196	814 ± 488	284 ± 306	345 ± 135
Nov.	122 ± 130	994 ± 1,052	74 ± 73	26 ± 24	224 ± 242	14 ± 19	192 ± 348	210 ± 149	222 ± 150	74 ± 88	215 ± 109
Average	119	637	31	16	459	34	70	140	383	124	204
D											
May	–	–	–	0	84 ± 67	0	0	8 ± 22	8 ± 16	38 ± 53	20 ± 13
Aug.	–	–	50 ± 108	40 ± 34	108 ± 73	36 ± 44	10 ± 22	30 ± 28	686 ± 314	190 ± 149	144 ± 76
Nov.	–	–	154 ± 290	92 ± 97	272 ± 87	88 ± 83	252 ± 239	292 ± 82	104 ± 73	88 ± 68	168 ± 44
Average	–	–	102	44	155	41	187	110	266	105	114
All sites[b]											
May	–	6 ± 6	4 ± 9	0 ± 0	111 ± 53	0 ± 0	6 ± 7	38 ± 33	76 ± 30	21 ± 14	30 ± 10
Aug.	196 ± 79	1,976 ± 1,185	17 ± 22	24 ± 12	963 ± 491	46 ± 20	28 ± 21	214 ± 118	1,150 ± 287	238 ± 90	454 ± 132
Nov.	276 ± 132	3,027 ± 1,375	140 ± 76	164 ± 102	527 ± 304	51 ± 33	276 ± 113	358 ± 132	558 ± 312	132 ± 58	493 ± 152
Average	236	1,670	58	63	534	32	103	204	595	130	336

[a] Annual averages (clams/m²) pooling the May, August, and November samples.

[b] Average abundance of clams, pooling the four sites.

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	32	103	204	595	130	336

[a] Annual averages (clams/m²) pooling the May, August, and November samples.

[b] Average abundance of clams, pooling the four sites.

TABLE 4. Mean abundance (clams/m² ± 95% CI) of *Corbicula fluminea* in the 7 to 14 mm shell length size-classes at each sampling site near the Connecticut Yankee power plant in the Connecticut River from August 1991 to November 2000.

Site	Years										All
Month	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	years
A											
May	–	112 ± 98	0	0	26 ± 30	0	0	0	44 ± 31	168 ± 286	39 ± 28
Aug.	338 ± 151	1,284 ± 926	8 ± 10	36 ± 38	1,154 ± 708	0	46 ± 38	142 ± 66	2,068 ± 1,185	290 ± 309	537 ± 224
Nov.	1,092 ± 584	5,172 ± 2,417	100 ± 97	120 ± 65	1,552 ± 786	22 ± 34	176 ± 104	786 ± 458	2,290 ± 1,484	736 ± 219	1,204 ± 472
Average[a]	715	2,189	36	52	911	7	74	309	1,467	398	612
B											
May	–	16 ± 29	0	0	2 ± 6	0	0	2 ± 6	6 ± 11	28 ± 24	6 ± 4
Aug.	118 ± 75	198 ± 96	18 ± 31	24 ± 7	702 ± 51	18 ± 16	22 ± 14	40 ± 25	520 ± 156	72 ± 34	173 ± 67
Nov.	72 ± 91	518 ± 68	36 ± 17	24 ± 41	926 ± 962	16 ± 17	52 ± 10	104 ± 61	918 ± 419	204 ± 240	287 ± 122
Average	95	244	18	16	543	11	25	49	481	101	161
C											
May	–	16 ± 29	0	0	8 ± 6	0	2 ± 6	0	22 ± 14	12 ± 16	6 ± 4
Aug.	154 ± 87	226 ± 60	22 ± 10	62 ± 39	928 ± 497	12 ± 14	30 ± 9	76 ± 42	770 ± 315	92 ± 76	237 ± 98
Nov.	368 ± 60	724 ± 145	66 ± 19	58 ± 58	926 ± 467	20 ± 15	28 ± 22	118 ± 68	730 ± 334	70 ± 77	310 ± 104
Average	261	322	29	40	621	11	20	65	507	58	191
D											
May	–	–	–	0	14 ± 27	0	4 ± 11	0	0	20 ± 25	5 ± 5
Aug.	–	–	24 ± 11	54 ± 35	646 ± 258	12 ± 16	18 ± 16	48 ± 38	608 ± 159	52 ± 24	183 ± 87
Nov.	–	–	48 ± 32	36 ± 47	292 ± 362	58 ± 32	42 ± 27	150 ± 42	804 ± 155	96 ± 73	190 ± 87
Average	–	–	36	30	317	23	21	66	471	56	132
All sites[b]											
May	–	48 ± 36	0	0	12 ± 8	0	2 ± 2	1 ± 1	18 ± 10	57 ± 59	15 ± 8
Aug.	203 ± 71	569 ± 365	18 ± 7	44 ± 13	858 ± 184	10 ± 6	29 ± 9	76 ± 25	991 ± 371	126 ± 72	288 ± 70
Nov.	510 ± 284	2,138 ± 1,360	62 ± 22	60 ± 26	924 ± 320	29 ± 12	74 ± 34	290 ± 160	1,186 ± 412	276 ± 142	514 ± 141
Average	357	918	29	34	598	13	35	122	732	153	282

[a] Annual averages (clams/m²) pooling the May, August, and November samples.

[b] Abundance of clams, pooling the four sites.

TABLE 5. Mean abundance (clams/m² ± 95% CI) of *Corbicula fluminea* in the 19 to 31 mm shell length size-classes at each sampling site near the Connecticut Yankee power plant in the Connecticut River from August 1991 to November 2000.

Site	Years										All
Month	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	years
A											
May	–	2 ± 6	0	0	0	0	2 ± 6	0	0	0	0.4 ± 0.6
Aug.	0	22 ± 27	0	0	16 ± 26	0	0	0	10 ± 12	8 ± 10	6 ± 3
Nov.	30 ± 51	62 ± 58	0	0	142 ± 184	0	2 ± 6	2 ± 6	34 ± 68	8 ± 10	28 ± 18
Average[a]	15	29	0	0	53	0	1	1	15	5	12
B											
May	–	0	0	0	0 ± 0	0	0	0	0	0	0
Aug.	0	16 ± 21	0	0	6 ± 8	0	0	0	2 ± 6	0	2 ± 2
Nov.	14 ± 27	8 ± 16	2 ± 6	4 ± 7	94 ± 22	0	0	0	6 ± 7	0	13 ± 8
Average	7	8	1	1	33	0	0	0	3	0	5
C											
May	–	0	0	0	0	0	0	0	0	0	0
Aug.	0	30 ± 23	0	0	10 ± 9	0	0	0	6 ± 11	0	5 ± 3
Nov.	18 ± 16	62 ± 16	0	0	34 ± 37	0	0	2 ± 6	4 ± 7	0	12 ± 6
Average	9	31	0	0	15	0	0	1	3	0	6
D											
May	–	–	–	0	0	0	0	0	0	0	0
Aug.	–	–	0	0	0	0	2 ± 6	0	6 ± 11	0	1 ± 1
Nov.	–	–	12 ± 10	2 ± 6	16 ± 19	0	0	0	14 ± 7	8 ± 6	7 ± 3
Average	–	–	6	1	5	0	1	0	7	3	3
All sites[b]											
May	–	0.7 ± 1.4	0	0	0	0	0.5 ± 1	0	0	0	0.1 ± 0.2
Aug.	0	23 ± 10	0	0	8 ± 6	0	0.5 ± 1	0	6 ± 4	2 ± 2	4 ± 1
Nov.	21 ± 15	44 ± 21	4 ± 3	2 ± 2	72 ± 41	0	0.5 ± 1	1 ± 1	15 ± 13	4 ± 13	15 ± 6
Average	10	22	1	1	26	0	1	<1	7	2	6

[a] Annual averages (clams/m²) pooling the May, August, and November samples.

[a] Abundance of clams, pooling the four sites.

TABLE 6. Mean abundance (clams/m² ± 95% CI) of *Corbicula fluminea* in the CY discharge canal (Site E) by size class from August 1991 to November 2000.

Year	Month	Abundance by size-class 2–4 mm	7–14 mm	19–31 mm	Total abundance
1991					
	May	–	–	–	–
	Aug.	34 ± 63	0	0	34 ± 63
	Nov.	172 ± 181	6 ± 17	0	178 ± 195
	Year's average	103	3	0	106
1992					
	May	2 ± 6	0	0	2 ± 6
	Aug.	12,174 ± 32,688	0	0	12,174 ± 32,688
	Nov.	96 ± 131	0	0	96 ± 131
	Year's average	4,091	0	0	4,091
1993					
	May	8 ± 10	24 ± 29	0	32 ± 24
	Aug.	0	0	0	0
	Nov.	32 ± 33	10 ± 18	0	42 ± 28
	Year's average	13	11	0	25
1994					
	May	0	0	0	0
	Aug.	36 ± 36	24 ± 29	0	60 ± 59
	Nov.	816 ± 1,303	58 ± 57	6±17	880 ± 1,354
	Year's average	284	27	2	313
1995					
	May	24 ± 31	0	0	24 ± 31
	Aug.	38 ± 54	0	0	38 ± 54
	Nov.	90 ± 202	0	0	90 ± 202
	Year's average	51	0	0	51
1996					
	May	0	8 ± 6	0	8 ± 6
	Aug.	48 ± 81	0	0	48 ± 81
	Nov.	10 ± 12	34 ± 81	0	44 ± 75
	Year's average	19	14	0	33
1997					
	May	60 ± 79	32 ± 31	0	92 ± 66
	Aug.	0	6 ± 17	0	6 ± 17
	Nov.	4 ± 7	18 ± 10	2 ± 6	24 ± 7
	Year's average	21	19	1	41
1998					
	May	18 ± 20	2 ± 6	0	20 ± 23
	Aug.	40 ± 81	16 ± 32	6±11	62 ± 89
	Nov.	106 ± 213	96 ± 77	10±12	212 ± 245
	Year's average	55	38	5	98
1999					
	May	74 ± 35	2 ± 6	0	76 ± 40
	Aug.	4 ± 7	216 ± 196	14 ± 17	234 ± 186
	Nov.	0	124 ± 148	86 ± 92	210 ± 79
	Year's average	26	114	33	173

TABLE 6. Continued

Year	Month	Abundance by size-class 2–4 mm	7–14 mm	19–31 mm	Total abundance
2000					
	May	0	4 ± 11	0	4 ± 11
	Aug.	20 ± 34	8 ± 16	2 ± 6	30 ± 38
	Nov.	162 ± 125	96 ± 100	10 ± 22	268 ± 195
	Year's average	61	36	4	101
10-year average					
	May	21 ± 11	8 ± 5	0	29 ± 12
	Aug.	1,239 ± 2,380	27 ± 22	2 ± 2	1,269 ± 2,378
	Nov.	149 ± 111	44 ± 19	11 ± 10	204 ± 116
	Annual average	485	27	5	517

TABLE 7. Average percentage winter survival of Asiatic clams (*Corbicula*), native clams (Sphaeridae), and native mussels (Unionidae) at four CY sampling sites.

Site	*Corbicula*	Sphaeridae	Unionidae
A	9.9%	47.0%	17.5%
B	9.3%	65.6%	51.3%
C	10.4%	28.5%	33.3%
D	12.7%	28.4%	–
Average	10.6%	42.4%	34.0%

gonadal tissues from May through January (Figure 5). The frequency of clams with eggs ranged from 75% to 100% and with sperm ranged from 52% to 100%. The presence of young in the demibranchs (brooding) and the active releasing of juveniles occurred from June to October. The frequency of clams brooding during this period ranged from 4% in October to 62% in August (Figure 5). In the 4 years of the reproduction study, only one brooding clam was observed in October and three in January. The periods of brooding and release of juvenile clams (spawning) occurred at about the same time, from June to September. Spawning peaked in August with an average release of 2,861 juveniles/clam/d.

During power plant operation, the clams were able to survive in the CY discharge canal from November through May; eggs and sperm were continually present in gonadal tissues (Figure 6). Eggs were present in 100% of clams surveyed and sperm frequency ranged from 8% in Decem-

TABLE 8. Spearman correlation coefficients of percentage winter survival of *Corbicula fluminea* at CY sites versus four indices of winter severity for the Connecticut River from 1992 through 2000[a].

Winter severity index	(Avg. ± SE)	Spearman correlation coefficients by site A	B	C	D	All sites combined
Average winter temp.[b]	(2.93°C ±0.37)	+0.92**	+0.73*	+0.84*	+0.63 ^{ns}	+0.87**
No. days ≤1 °C	(54.9 d ±8.75)	–0.87**	–0.63 ^{ns}	–0.74 ^{ns}	–0.56 ^{ns}	–0.73*
No. days ≤2 °C	(70.6 d ±8.12)	–0.82*	–0.52 ^{ns}	–0.62 ^{ns}	–0.67 ^{ns}	–0.65 ^{ns}
April flow ≥1,700 m^3/s[c]	(6.4 d ±1.54)	–0.74*	–0.78*	–0.73 ^{ns}	–0.69 ^{ns}	–0.91**

[a] 1993 data were omitted because of the mortality caused by the March storm Joshua (see text).
[b] Average winter temperature = the annual Dec.–Apr. mean daily Connecticut River temperature at CY.
[c] Number of days in April when the Connecticut River flow equaled or exceeded a daily average of 1,700 m^3/s.
Significance levels: ** = $P < 0.01$; * = $P < 0.05$; ns = $P \geq 0.05$.

Total abundance
4 ± 11
30 ± 38
268 ± 195
101
29 ± 12
1,269 ± 2,378
204 ± 116
517

e to October. The luring this period !% in August (Fig- production study, served in October s of brooding and ning) occurred at ne to September. th an average re-

n, the clams were harge canal from and sperm were l tissues (Figure f clams surveyed m 8% in Decem-

a at CY sites versus

	All sites combined
ns	+0.87**
ns	−0.73*
ns	−0.65 ns
ns	−0.91**

: at CY.
e of 1,700 m³/s.

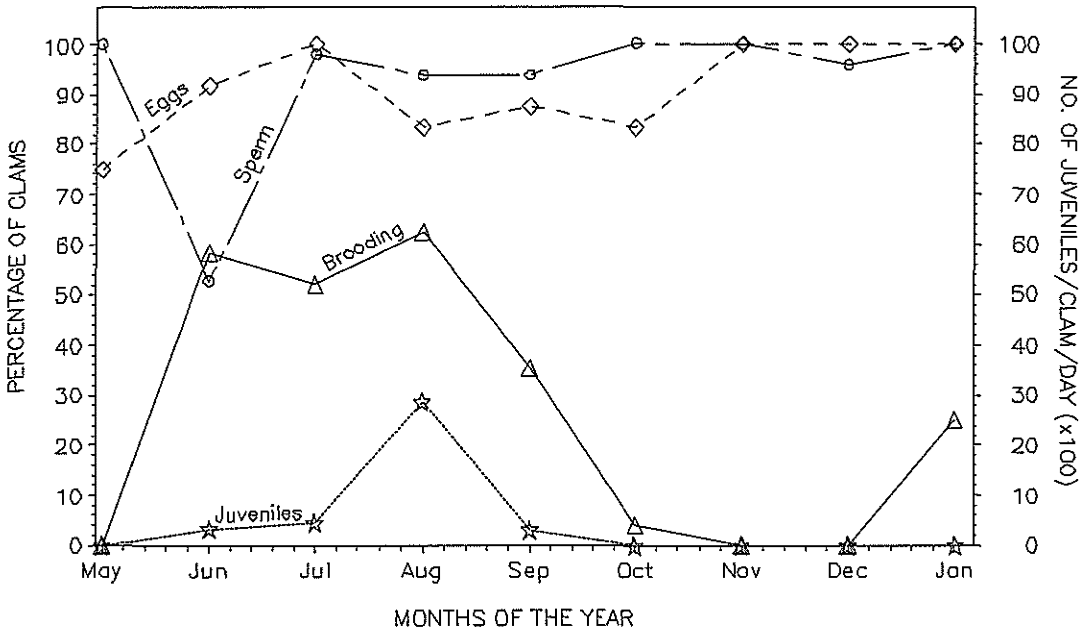

FIGURE 5. Average seasonal reproductive status of *Corbicula fluminea* (1991-1994) at ambient river temperatures. The percentage of adult clams (≥8 mm) with mature gametes or brooding young is plotted using the left axis. Active spawning is plotted using the right axis and is defined as the average number juveniles released over a 24-h period by 12 randomly selected adult clams.

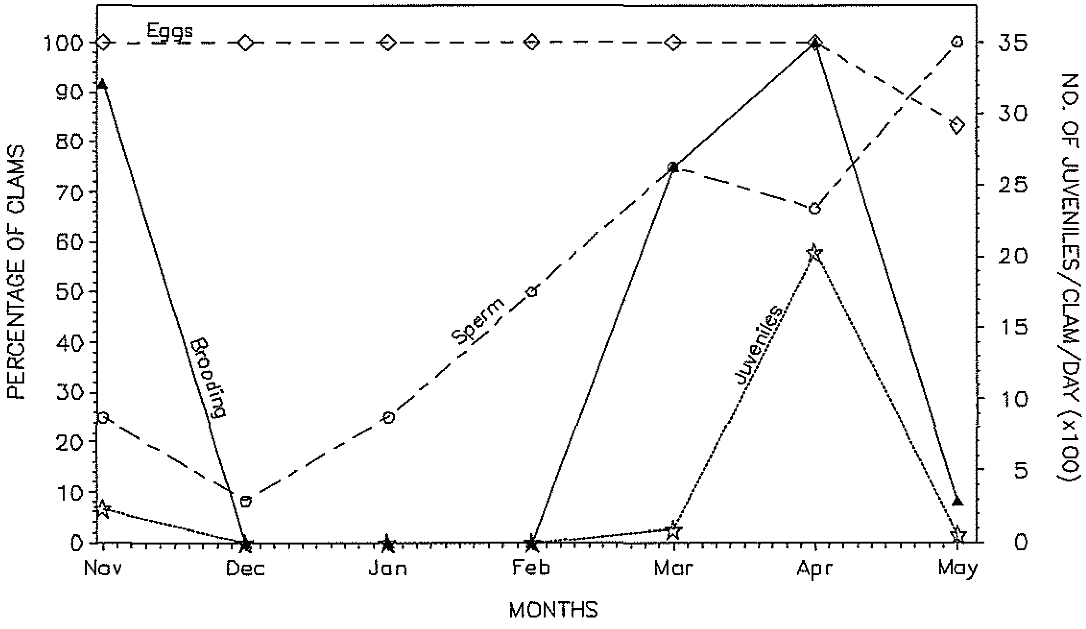

FIGURE 6. Reproductive status of *Corbicula fluminea* held in the CY discharge canal from November 1992 to May 1993, when water temperatures were 8°C to 12°C above ambient river temperatures. The percentage of adult clams (≥8 mm) with mature gametes or brooding young is plotted using the left axis. Active spawning is plotted using the right axis and is defined as the number juveniles released over a 24-h period by 12 randomly selected adult clams.

ber to 100% in May. Continuous brooding and spawning occurred from March through May with brooding adults ranging from 8% to 100%, when water temperature averaged ≥17°C. Brooding and spawning were also observed in November (92% brooding), when temperatures averaged 18.3°C. The sharp decrease in spawning activity in May was the result of power plant shut down beginning on 15 May 1993, which dropped cooling water temperatures from 30°C to 18°C in a single day. Brooding and spawning peaked in June and July as the power outage continued and reproduction of discharge clams followed the pattern observed at ambient river temperatures (17–21°C). On 21 July 1993 the power plant restarted and temperatures increased to >35°C in 4 d. All clams held in the CY discharge canal were dead by 18 August 1993.

Growth

Quadratic regression models fit to captive clam growth data had slope parameters (b1 and b2) that were significantly different from zero ($P < 0.05$; Figure 7). The 1991 growth data showed the best fit to the model ($R^2 = 0.96$) and had the highest peak growth rate of 1.08 mm/week. Peak growth rates in 1992 and 1993 were 0.68 mm/week and 0.44 mm/week, respectively. *Corbicula* growth under ambient conditions during 1991–1993 exhibited seasonal cycles. For example, growth in 1991 between June and July was 1.08 mm/week, between July and August was 0.94 mm/week, and between August and September was 0.60 mm/week. Growth was minimal from September to October (0.10 mm/week) and October to November (0.06 mm/week).

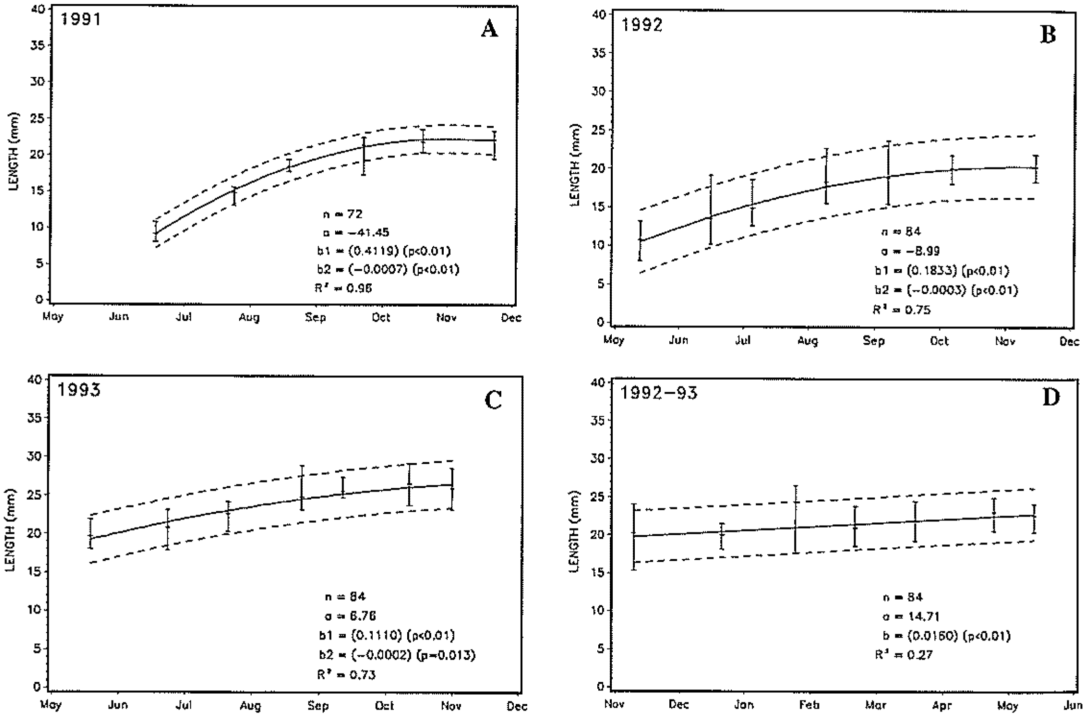

FIGURE 7. Growth of *Corbicula fluminea* at ambient river conditions in 1991, 1992 and 1993 (Panels A–C), as compared to growth at CY discharge (Panel D) conditions from November 1992 to August 1993. The quadratic regression models (1991, 1992, and 1993) are of the form, Length = a + b1(Day) + b2(Day)^2, where "a" is the intercept, "b1" and "b2" are the slopes, and "Day" references the Julian day of the year for 1991, 1992, and 1993. The linear regression model (1992–1993) is of the form, Length = a + b(Day), where "Day" references a cumulative Julian day over the 2-year period 1992–1993. Regression lines are bracketed by 95% confidence limits, and the vertical bars indicate the minimum, maximum, and average shell length by horizontal bars ($n = 12$).

Clam growth in the CY discharge canal was 0.05 mm/week from November 1992 to February 1993, when water temperatures ranged from 12–21°C (10–12°C above ambient river temperatures; Figure 7). Increased growth rates were observed from February to May (0.14 mm/week), when water temperatures ranged from 12–30°C. Maximum growth rates at this site occurred from May to July (0.36 mm/week), when canal temperatures were similar to those at ambient river sites because of a power plant shut down. All clams died after the power plant restarted in July 1993 and discharge water temperatures exceeded 37°C.

Native Bivalve Abundance

Clams of the family Sphaeridae comprised more than 90% of the native bivalves collected and were not identified below this taxonomic level, while adult mussels (Unionidae) were identified to species. Four mussel species were documented at the Connecticut River sites: eastern elliptio *Elliptio complanata*, alewife floater *Anodonta implicata*, tidewater mucket *Ligumia ochracea*, and eastern pondmussel *L. nasuta*. Of these, *E. complanata* comprised more than 90% of all mussels collected. *Ligumia ochracea* and *L. nasuta*, the rarest mussels, were not collected until 1997 and 1999, respectively.

Mean annual abundances (individuals/m^2) of native clams and mussels were highly variable with clams ranging from 16 to 242 and mussels ranging from 1 to 5 (Figure 8). Abundances of both mussels and clams were highest in 1991. The lowest abundances for clams occurred in 1993, 1996, and 2000, while those for mussels occurred in 1995 and 2000. Mean annual abundances of native clams (Sphaeridae) averaged six times lower than those for *Corbicula*.

Winter survival was considerably greater for native clams and mussels than for *Corbicula* (Table 7). Winter survival of Sphaeridae ranged

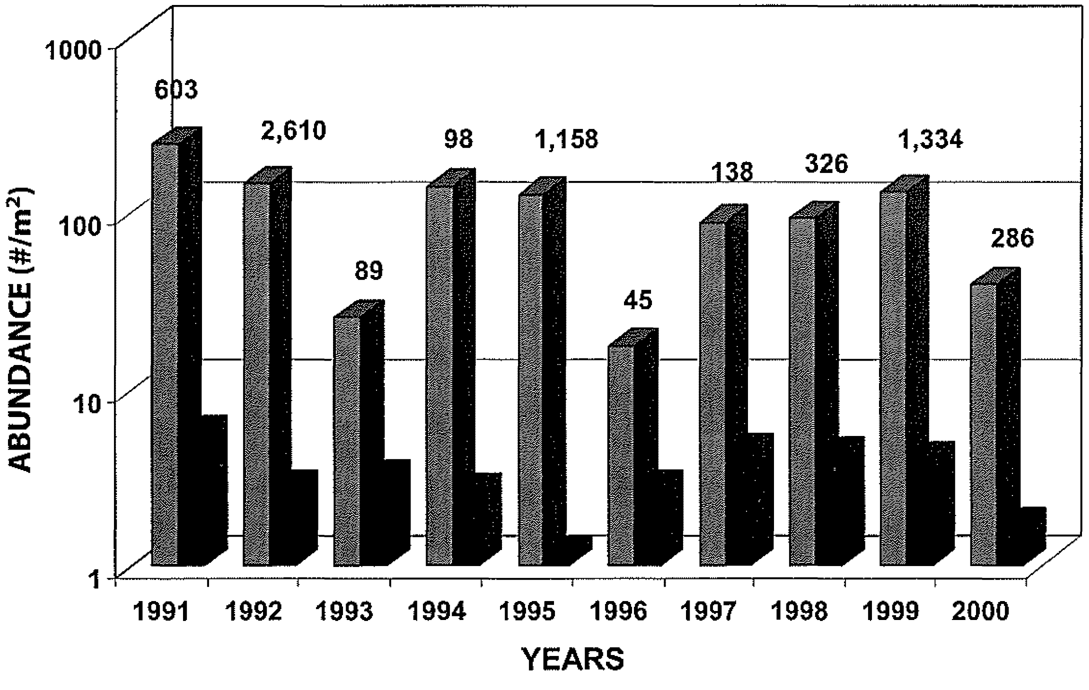

FIGURE 8. Annual abundance ((#/m^2)+1) of native clams (Sphaeridae) and mussels (Unionidae) from 1991 through 2000 at Connecticut River sites in the vicinity of CY. Annual abundance estimates for *Corbicula* are given in numeric values (#/m^2) above each year.

from 28.4% at D to 65.6% at B, averaging 42% for all sites. Unionidae survival ranged from 17.5% at A to 51.3% at B, averaging 34% for sites A–C. Mussels were not collected at D. In comparison, *Corbicula* survival ranged from 9.3% at B to 12.7% at D, averaging 11% overall.

Statistical trend analyses on the log transformed abundance data using a Mann-Kendall statistic showed no significant ($P < 0.05$) trends in abundance for either native clam or mussels from 1991 to 2000. *T*-tests of native clam and mussel seasonal abundance during the CY operational period (1991–1996) versus the pos-operational period (1997–2000) showed no significant differences, except for mussels in November (Table 9).

Discussion

Corbicula has been a major component of macrobenthic communities in the lower Connecticut River following its initial discovery in 1990. *Corbicula* distribution in 1991 extended northward from CY to Gildersleeve Island, a 16 km section of the river, and it spread 22 km further upriver in 1992. Savoy and Benway (2004, this volume) collected sediment grab samples during 2000–2002 approximately 5–10 km upriver from the northern extent reported for *Corbicula* in 1992 (South Meadow station) and did not report the presence *Corbicula.* Upstream movements of *Corbicula* are not unusual and can happen without anthropogenic intervention (Voelz et al. 1998). Rodgers et al. (1977) reported movement of 222 km in 15 years. Once a *Corbicula* population is established upriver, downriver dispersal is more rapid; the clams are able to free themselves from the bottom and are aided by water currents in their movements (Sinclair and Isom 1963; Britton and Morton 1979; Eng 1979; Prezant and Chalermwat 1984; French and Schloesser 1996).

Corbicula winter survival in the Connecticut River was correlated positively with water temperature from December through April, and negatively with high-water flows in spring. No clams survived at any of the sites during the coldest winters of 1993–1994 and 1995–1996, when temperatures were below 2°C for 12–15 weeks. Similarly low survival due to coldwater temperatures was reported by a number of other researchers (Horning and Keup 1964; Bickel 1966; Dreier 1977; Rodgers et al. 1979; Cherry et al. 1980; Graney et al. 1980; Cairns and Cherry 1983). *Corbicula* survival at individual stations was also influenced by distance from the thermal plume discharge. Winter survival at site D, the river site nearest to where the CY discharge mixes with the river, was not significantly correlated with winter water temperature indices. The sites between the CY intakes and discharge canal (sites B and C) were significantly correlated with average winter water temperatures, but not correlated with the number of days water temperatures below 1°C or 2°C. The reason for the poor correlation of these temperature indices (≤2°C and ≤1°C) at sites B, C, and D might be related to the thermal plume mixing with ambient temperature river water during tidal incursions into our sampling sites or the

TABLE 9. Total abundance of *Corbicula fluminea*, native clams (Sphaeridae), and native mussels (Unionidae) in relation to the CY power plant's operational status.

		C. fluminea		Sphaeridae		Unionidae	
Month	Time	Mean[a]	SE	Mean	SE	Mean	SE
May	Operational[b]	37.22	8.48	39.11	13.00	1.22	0.47
	Post-operational[c]	54.50	9.70	45.75	11.49	2.12	0.58
August	Operational	733.33	142.29	147.54	21.90	3.18	0.83
	Post-operational	715.50	120.76	119.00	23.50	1.75	0.50
November	Operational	1,190.09	235.71	110.46	25.77	**0.91	0.42
	Post-operational	792.62	106.96	94.25	16.56	**4.00	1.15

[a] Mean = #/m^2 is calculated by averaging the total number of individuals per grab at the A, B, C, and D for each sample month from 1991 to 2000 and converting that value to #/m^2 ((#/grab) × 10).

[b] CY operational years (1991–1996).

[c] Post-operational years (1997–2000).

** Difference in abundance between time periods is highly significant; Satterthwaite *t*-test, $P < 0.01$.

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Unionidae	
Mean	SE
1.22	0.47
2.12	0.58
3.18	0.83
1.75	0.50
**0.91	0.42
**4.00	1.15

ınd D for each

.01.

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recruitment of some CY discharge canal clams to these sites closest to the discharge outfall. However, *t*-tests of winter survival data at each site between operation and postoperational years indicated no differences. Although twice each day during low flow conditions the river reverses flow and thermal plume water moves upriver where our sites are located (Rozsa 2001; Boyd 2004 [1976]), differences in site correlations to winter severity indices could be caused by site locations in relation to river conditions other than CY discharge effects. The significant correlations observed at site A between river temperature indices and winter survival of clams indicates no thermal plume effects at this station. During periods of high river flow, usually in the spring and other times of flooding, the flow at CY is unidirectional and not influenced by tidal flows. The *Corbicula* population at CY sites was able to recover after high winter mortalities by August and usually peaked in November. This recovery was driven by passive downriver recolonization from populations that were able to survive the cold winter conditions in refugia (e.g., those known to exist near thermal plumes at Middletown and possibly South Meadow power stations or natural refugia, such as groundwater seeps) (Morgan et al. 2003).

The importance of CY thermal discharge as a refuge for *Corbicula* survival in the Connecticut River during cold winters appears minimal. The clams were not able to maintain year-round popu-lations in the discharge canal because of total mortality due to high discharge temperatures from June through October. Most *Corbicula* that could colonize the discharge canal in winter and spring, therefore, were small and not reproductively ma-ture. If movement of clams to the river sites oc-curred during March through May, it would occur when conditions were poor for their survival (e.g., low spring water temperatures [<12°C] and high, unidirectional spring flows).

Additional evidence that the CY discharge was not necessary for survival of *Corbicula* popu-lations in the Connecticut River is apparent when *Corbicula* abundance during CY operation (1991– 1996) was compared to abundance following the plant closure (1997–2000). Following closure of the CY power plant in 1996, the abundance of *Corbicula* at all sites was not significantly differ-ent than during the operational period. In addi-tion, following CY closure, clams were able to survive in the discharge canal throughout the year and significant increases in the abundance of larger size clams were observed.

The growth patterns of *Corbicula* in the Connecticut River are similar to those reported by other researchers. The highest growth rate occurred in the summer at temperatures approximating 25°C, and minimal growth occurred at temperatures below 15°C. Others have reported 10–15°C to be the lower threshold for *Corbicula* growth (Joy 1985; Mattice and Wright 1986; McMahon and Williams 1986a; Stites et al. 1995).

The high *Corbicula* growth rate in 1991 was due to small-sized individuals used in the study. Other researchers have also reported that smaller clams have higher growth rates (O'Kane 1976; Britton et al. 1979; Mattice 1979; Dreier and Tranquilli 1981; Dauble et al. 1985; Joy 1985; Mattice and Wright 1986; McMahon and Williams 1986a, 1986b; Foe and Knight 1986; Morgan et al. 2003). The total growth of *Corbicula* in the Connecticut River was in the range of growth reported by others (Britton et al. 1979; McMahon 1983; Welch and Joy 1984; Mattice and Wright 1986; McMahon and Williams 1986a; French and Schloesser 1991). The growth of *Corbicula* at the CY discharge started in the fall and continued modestly until discharge water temperatures exceeded 37°C in June or July, when all clams died. Others reported that the upper temperature tolerance threshold for this clam between 34–37°C (Mattice and Dye 1976; Dreier 1977; Mattice 1979; Cairns and Cherry 1983; McMahon 1983; McMahon and Williams 1986b).

Brooding and spawning of *Corbicula* in the Connecticut River and CY discharge canal occurred at water temperatures between 15°C and 31°C. Ambient river temperatures remained within this range from June to September, and CY discharge conditions remained within this range in November and April to mid-May. Peak reproduction, as described by brooding and spawning, occurred in August at river temperatures (22–28°C) and in April at CY discharge temperatures (13–24°C). The survival of juveniles released in the discharge canal is questionable, particularly during times of high water flow. Potential recruitment to the river from the discharge canal comes when temperature in the river is low for successful growth and river flow rates are at yearly optimal levels for downriver transport by the swift, unidirectional currents of spring freshets. As a result, they would be exposed to estuarine waters of Long Island Sound and perish due to high salinity.

While *Corbicula* quickly established itself as the dominant bivalve in the Connecticut River, there was little change in native bivalve abundance found in the same sediments. We believe this is due to relatively high winter survival of native clams and mussels when compared to that for *Corbicula*. Similarly, Fuller and Imlay (1976) questioned whether there was any displacement of native Unionidae species following *Corbicula* colonization. Diaz (1994) concluded that *Corbicula* invasions of Northern American tidal freshwater systems in the late 1960s did not displace tidal freshwater species, but rather, these nonnative clams took advantage of underutilized benthic resources. Others suggest filtration activities by high densities of *Corbicula* can lead to alteration of nutrient dynamics in aquatic systems, resulting in negative impacts on native bivalves (Kraemer 1979; Lauritsen 1986; Leff et al. 1990; Phelps 1994). Karatayev et al. (2003) found no correlations between the densities of *Corbicula* and other benthic invertebrates in an East Texas lake.

Low densities of native clams and mussels in the Connecticut River may suggest availability of an unoccupied niche for *Corbicula* to colonize. In addition, high water flow of the Connecticut River may provide a steady supply of nutrients and food for filter feeders, further limiting the effects of *Corbicula* on native species.

Conclusion

Within 2 years of their discovery in the Connecticut River, *Corbicula* colonized 38 km of river upstream of the CY plant. The *Corbicula* population in the vicinity of the CY plant was highly variable within and between years. However, annual densities during plant operation in 1991–1996 were not significantly different from those following the plant closure in 1997–2000. This suggests that the CY thermal discharge did not serve as an important refuge area for *Corbicula* overwintering in the vicinity of the plant. Continuous chlorination (at <0.10 ppm) was effective in preventing *Corbicula* from fouling service water systems at CY. The lack of correlation between presence of *Corbicula* and abundance of native clams and mussels suggest no detrimental effect of *Corbicula* on native species in the Connecticut River during these studies. Finally, the success of *Corbicula* in more northerly ranges of New England may not always be associated with the thermal plumes from industrial facilities, but could also result from other thermal refugia such as groundwater seeps that are above 2°C.

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