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USE OF LARVAL STOCKING IN RESTORATION OF PELAGIC-SPAWNING ANADROMOUS FISHES

by

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ABSTRACT

The Atlantic coast population of striped bass *Morone saxatilis* collapsed in the late 1970s. Hatchery programs and release experiments were instituted to evaluate the potential to restore striped bass in Chesapeake Bay. Because survival of striped bass larvae to first feeding (7 days after hatch) is low, ranging from 0.2% to 5.2%, it may be feasible to enhance survival through hatchery propagation of eggs and yolk-sac larvae, and to supplement recruitment by stocking post-yolk-sac larvae. During 1991-1993, otoliths of 31.7 million hatchery-produced striped bass larvae (5-13 days after hatch) were chemically marked and released into two tributaries of the Chesapeake Bay. In years of moderate to poor natural survival (1991, 1992), stocked larvae contributed substantially (20 to 30%) to overall juvenile abundance. In 1993, a year of high natural production, stocked larvae contributed only 5% to juvenile abundance, although numbers contributed were higher than in previous years. Using field and hatchery estimates of larval and juvenile growth and mortality, we contrasted enhancement strategies in which fish were released at three different ages: larvae (7 days after hatch), Phase I juveniles (55 days after hatch), or Phase II juveniles (220 days after hatch). Cohort biomass accumulation was highest when Phase I juveniles were stocked. Hatchery-reared juveniles experienced substantially higher rates of growth and survival than did wild juveniles of similar age. When approximate costs were incorporated into the analysis, the efficacy of larval stocking to increase cohort biomass was approximately equivalent to stocking Phase I juveniles. During years of poor recruitment larval stocking in estuarine tributaries could supplement stocks of striped bass and other anadromous species which experience high embryo and yolk-sac larva mortality.

Keywords: anadromy, hatchery stocking, larval stocking, otolith, recruitment, striped bass.

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INTRODUCTION

Striped Bass Restoration

Large reductions in landings of striped bass *Morone saxatilis* and declines in recruitment (Fig. 1) prompted a restoration program in the Chesapeake Bay (ASMFC 1995). Tagging and genetic studies had shown that Chesapeake Bay is the major nursery area and source of recruits to coastal fisheries in the mid-Atlantic region of North America (Boreman and Lewis 1987; Fabrizio 1987; Wirgin et al. 1993). High rates of exploitation on premigratory juveniles ($Z > 2.0$ yr^{-1}; Gibson 1993) throughout the 1970s and degraded nursery habitats (Hall et al. 1993) were believed to have led to recruitment failure in Chesapeake Bay. One of two principal responses by management to restore striped bass was a hatchery-based stocking program. From 1985-1993, 1.4 million "Phase I" juveniles (35-50 mm, total length [TL]) and 6.1 million "Phase II" juveniles (150 to 200 mm TL) were stocked into several Chesapeake Bay tributaries (Fig. 2). The other response was to impose moratoria in Maryland (1985-1989) and Virginia (1989), and restrict exploitation in coastal waters (ASMFC 1995).

The rationale for hatchery-based restoration was based upon studies that indicated: 1) high mortality rates of eggs and larvae in nursery habitats; and 2) strong environmental effects on striped bass recruitment (e.g. Ulanowicz and Polgar 1980). In two Chesapeake tributaries, recent estimates of larval mortality to first feeding (ca. 5 days after hatch) ranged from 94.8 - 99.8%; larval mortality from first-feeding to ca. 8 mm standard length ranged from 91.6 - 94.8% (Secor and Houde 1995a; Kellogg et al. 1996).

Low striped bass larval survivorship in degraded nursery habitats was proposed by Hall et al. (1993) as the "acidification hypothesis." Laboratory and *in situ* studies in several tributaries of Chesapeake Bay indicated that acid rain depressed pH in nursery habitats and mobilized toxic metals, at concentrations lethal to striped bass larvae. Alternatively, ichthyoplankton studies demonstrated that metereologically driven variability in water quality (temperature, pH, conductivity) are dominant influences on egg and larval survival and juvenile production (Uphoff 1989; Rutherford and Houde 1995; Secor and Houde 1995a; Kellogg et al. 1996). Thus, if survival of embryos, and survival and growth of larvae, were high in hatcheries, then released juveniles would have bypassed a bottleneck of critical mortality, whether caused by degraded nursery habitat or fluctuating meteorological conditions.

In this paper, we examine the premise that stocking striped bass juveniles is a superior strategy to stocking larvae. We have conducted larval mark-recapture experiments in three years (1991-1993) and in two tributaries, the Patuxent and Nanticoke Rivers (Fig. 3), to examine how vital rates of larvae are related to meteorological events and associated water quality (Secor et al. 1995a, b; 1996). Our experiments indicated that larvae released under favorable conditions made substantial contributions to juvenile production. Therefore, stocking larvae as a replenishment tool might be a viable alternative to stocking juveniles. Here, we first document the contribution of hatchery stocked striped bass larvae to juvenile populations in the Patuxent and Nanticoke Rivers in 1991-1993. We then apply estimated larval growth and survival rates from past studies and the literature to compare production rates of striped bass larvae and juveniles in either wild or hatchery environments. Three ages at release were examined: 7-d posthatch, first-feeding larvae; 55 day posthatch, "Phase I" juveniles; and 220 day posthatch, "Phase II" juveniles. Criteria considered were rates of biomass accumulation, cost, and genetic representation (number of spawning females producing an annual cohort).

METHODS

Larval Mark-recapture Experiments

Striped bass eggs, obtained from induced spawning in the hatchery of 10 (1991), 8 (1992) and 12 (1993) wild females captured in the Patuxent (1991) or Nanticoke River (1992-1993), were provided to us by Maryland Department of Natural Resources (Table 1). Fertilized eggs were held in 1-2 m^3 raceways for incubation and larval rearing at the Manning Hatchery. Larvae were immersed in solutions of alizarin complexone (ALC) in 1991 and 1992 and tetracycline hydrochloride (TC) in 1993 to produce fluorescent marks in their otoliths (Secor et al. 1991; Secor et al. 1995). Batches of embryos or larvae were immersed and marked at ages ranging from 0 to 9 days after hatch. Batches of larvae were marked by single or multiple treatments (Table 1). Otolith marks (equivalent to codes) on recaptured individuals provided information on release date, site, and larval age at release.

Six to 13 day-old larvae were transported from the hatchery to release sites and released directly into the rivers. Release sites were chosen based upon occurrences of wild striped bass larvae in collections during the week preceding the initial stocking date in each year. Tests at the Chesapeake Biological Laboratory (CBL) and at an on-site laboratory on the Nanticoke River (1992-1993) showed no increased mortality during a 24-h period associated with the stocking procedure (water quality changes) compared to control levels (larvae maintained under hatchery water quality conditions). Therefore, in the field experiments, larvae were not acclimated to river water prior to their release.

Recaptures of released larvae were obtained in several one-day ichthyoplankton surveys from late April to early June, following the first release of marked larvae. Sampling gears were a 60-cm plankton net and a 2-m^2 mouth-opening Tucker trawl. On each survey date, collections were made at 8 to 11 stations spanning the known nursery area of wild striped bass larvae. Secor et al. (1995; 1996) provide details on methods and analysis of ichthyoplankton samples and water quality datasets. Juvenile striped bass were surveyed by Maryland Department of Natural Resources in 37-m seine collections from 13 July to 15 September in all years. Three surveys were conducted annually at six (Patuxent River) and eight sites (Nanticoke River) that have been sampled historically to index juvenile abundance (Minkkinen 1993).

Otoliths of larval and juvenile striped bass were examined (Secor et al. 1991b). The presence of marks on otolith increments was determined under an epifluorescence microscope. Identification of specific otolith marks (Table 1) allowed release date, larval age(s) at release, and sites of release (1992 experiment only) to be determined.

Growth and mortality rates of marked larvae were determined based upon their lengths, known ages and estimated abundances. Growth rates of larvae were estimated from exponential regressions of length on age (Ricker 1975). Growth and mortality rates from the exponential models were compared statistically among groups using a Newman-Keuls test (Zar 1974).

During June, the Maryland Department of Natural Resources released 105,915; 97,297 and 278,844 coded wire-tagged (CWT), young-of-the-year (40 - 60 mm SL) striped bass in 1991, 1992, and 1993, respectively (Minkkinen 1993). The number of juveniles stocked, adjusted for transport mortality and tag loss, was 97,611; 71,124 and 209,133 in 1991, 1992 and 1993, respectively. Based upon abundances of recaptured CWT juveniles and seined juveniles originating from our marked larval releases, we were able to estimate recruitment potential of our released larvae. Abundances of juveniles from our marked larval releases (N_{CM}) were estimated (Ricker 1975; Secor and Houde 1995b) by:

$$N_{CM} = \sum_{i=1}^{x} (N_{CWT} R_{CM_i}) R^{-1}_{CWT} \qquad (1)$$

where N_{CWT} = number of released juveniles with coded wire tag, adjusted for tag loss and stocking mortality;

i (1...x) = experimental larval release group;

R_{CM_i} = number of recaptured juveniles that had been released as larvae and coded for release i by the unique chemical mark on their otoliths;

R_{CWT} = number of coded wire-tagged juveniles recaptured in the juvenile sampling program.

Applying Equation 1, estimates of abundance of juveniles were obtained for each experimental larval release. The variance of abundance estimates of the otolith-marked juveniles was calculated based upon an assumed Poisson distribution (Ricker 1975). In 1991 and 1992, all larval release groups were identifiable based upon the unique marks and mark combinations on their otoliths. In 1993, only one of the individual release group (second release, larvae released at 12 d posthatch) could be confidently distinguished in the juvenile recaptures. Specific identification of other marked groups in 1993 would be depended upon very accurate (± 3 days) ageing, which was not possible based upon analysis of the juvenile otoliths in juveniles (Secor and Dean 1989).

Overall survival rate to the 40-60 mm stage for each release group (S_i) was estimated by:

$$S_i = N_{CM_i}(N_{o_i})^{-1} \qquad (2)$$

where N_{CM_i} = estimated number of 40-60 mm juveniles from experimental release i (eq. 1) and;

N_{o_i} = number of larvae stocked in experimental release *i* adjusted for mortality associated with the stocking procedure.

Cohort Biomass Production Model

The Chesapeake Bay striped bass stocking program has depended upon releases at either ca. 55 days after hatch (Phase I juveniles) or ca. 220 days after hatch (Phase II juveniles). We wished to compare these strategies with releasing larvae at first feeding (7 days after hatch). Therefore, stage-specific growth and mortality rates and weights were obtained for the following periods: -2.5 to 6 days after hatch (embryo), 7 to 55 days after hatch (larva), and 56 to 220 days after hatch (juvenile). Hatching was assumed to occur at 2.5 days after spawning (Secor et al. 1992). Estimates of vital rates and wet weights of wild larvae and juveniles were obtained from field studies in the Patuxent River (Secor and Houde 1995a; Secor et al 1995; Minkinnen and Stence 1993) and the Nanticoke River (Minkinnen 1993; Kellogg et al. 1996; Secor et al. 1996). Cohort-specific rates of larval-stage growth and mortality were available for all years. Estimated initial egg weight (1.0 mg) was obtained from Secor et al. (1992) for South Carolina striped bass because estimates for Chesapeake Bay striped bass were not available.

Estimates of vital rates and weights for hatchery-produced fish were calculated from data provided by the Potomac Electric Power Company which produced the Phase I and Phase II juveniles stocked into the Patuxent and Nanticoke River (PEPCO 1987-1995). Pond-specific rates of larval growth, mortality, and weight were available for several ponds in the period 1987-1995. Only mean values of juvenile survival and growth were reported in PEPCO documents. Wet weights at 7 d posthatch of hatchery-produced larvae stocked into the Nanticoke River were measured by Kellogg (1996).

Cohort, stage-specific biomass (B_S) was estimated as:

$$B_S = B_{S-1} \left[(W_S/W_{S-1})^{[1-(Z_S/G_S)]} \right] \quad (3)$$

where B_{S-1} biomass at the end of the previous stage, W_S and W_{S-1} are median weights at the end of stages S and S-1, and G_S and Z_S are daily instantaneous growth-in-weight and mortality rates for stage S. This method was adapted from Houde's (1996) model of biomass proliferation and allowed cohort biomass to be "fine-tuned" to expected stage-specific weights. To reduce the effects of outliers, median values were chosen to represent stage-specific vital rates and weights. In cases where 3 or fewer data were available, mean vital rates and weight values were used to estimate biomass.

In our comparison analysis, we adopted a model scenario which depended upon stocking a maximum biomass of juveniles (Phase I or Phase II) in a year of poor natural reproduction. B_0, the initial spawned biomass, was specified as 2 10^6 g for natural cohorts (egg production = 2 billion, ca. 1,000 spawning females). Field estimates of spawned egg biomass in the Patuxent and Nanticoke Rivers ranged between 0.7 and 6.7 million grams (Secor and Houde 1995; Kellogg et al. 1996). The modeled scenario represented a year of low egg production. Initial egg biomass in the hatchery was stipulated at 10^4 g (egg production = 10 million, ca. 5 spawning females). Ten million eggs ,or ca.

analyzed (1991 and 1992), the average cohort lost biomass during the larval stage (Fig. 5). However, several "weekly" cohorts (larvae spawned within the same 4-6 day period) during these years showed increases in cohort biomass (Secor and Houde 1995a; Kellogg et al. 1996; Houde 1996). For example, in the Patuxent River (1991) Secor and Houde (1995a) showed that high survival rates occurred when weekly cohorts experienced mean temperatures of 16-20°C during their first 25 days after hatch. In that year, larvae were stocked during a period followed by favorable temperatures. Alternatively, complete loss of release groups in our experiments provides critical insight on when and where not to stock larval striped bass. In 1993 (Nanticoke River), a storm event apparently caused in complete loss of larvae stocked on 24 April; no larvae or juveniles were recovered with a mark corresponding to this group (Secor et al. 1996). Similarly, in 1991, complete loss of an entire group of stocked larvae occurred because the release was downstream from the maximum turbidity zone which may serve as a retention front, delimiting the downstream boundary of striped bass nurseries (Secor et al. 1995; Secor 1996). Results from three years of ichthyoplankton surveys and larval mark-recapture experiments indicated that survival of released larvae often is substantially higher than that of average weekly cohorts of wild larvae if larvae are strategically released into favorable conditions. These conditions include: 1) periods of stable and rising temperatures between 16 and 20°C; 2) mean nursery alkalinity >15 mg/L as $CaCO_3$; pH>6.9; and 3) avoidance of storms, especially during dry years (Secor 1996).

Meterological forecasting and surveys of nursery water quality could increase the probability of stocking larvae into favorable conditions. However, weather during April and May is quite variable and not easily predicted, and hatchery-produced larvae of appropriate ages may not always be available to stock during favorable conditions. Despite these uncertainties, we believe that a long-term larval stocking program could, on average, augment natural striped bass juvenile abundances in poor to average years of natural recruitment.

<u>Stocking Strategy: Larvae or Juveniles?</u>

How efficient is larval stocking in comparison to stocking hatchery-produced juveniles? We addressed this question by assembling available data, estimating stage-specific vital rates and weights, and analyzing rates of biomass accumulation and hatchery contributions under scenarios of releasing larvae, Phase I juveniles or Phase II juveniles. Larval mortality rate estimates were the most variable (wild larvae) or uncertain (hatchery larvae). Therefore, these rates were deliberately varied to evaluate larval versus juvenile stocking strategies.

We believe that biomass estimates of wild striped bass at 55 d posthatch (Fig. 5) for the 1991-1993 annual cohorts may have been underestimated. Estimates (Secor and Houde 1995; Kellogg et al. 1996) of cohort abundances at 55 d posthatch were 14,930, 5,435 and 28,387 for 1991, 1992, and 1993, respectively. These estimates were one to nearly three orders of magnitude less than mid-July abundance estimates for juveniles at ca. 85 d posthatch (Table 3). Striped bass are difficult to sample and mortality rates are difficult to measure during the late larval and early juvenile period because of an ontogenetic habitat shift from freshwater pelagic to brackish benthic habitats. If mortality rates were lower during this period than we had estimated, substantially higher biomass gain compared to those predicted may have been realized. Finer scale resolution of ontogenetic changes in mortality and growth rates during the larval stage would probably result in higher biomass estimates at 55 d posthatch because the difference, G-Z, would be expected to increase with size (see Equation 3). Because of the uncertainties in estimating mortality rates during the larval stage, a prudent approach was one that considered several possible mortality rates in the field (Fig. 6).

The overall scenario for comparing wild and stocked biomass accumulation rates stipulated a low spawning year (egg production = 2 billion eggs) and hatchery production limited to five females or ca. 2.7 million 7-d posthatch larvae. Although many more larvae were actually stocked into the Patuxent and Nanticoke Rivers, this number represents a maximum number of larvae which could be initially reared to grow Phase I or Phase II juveniles at the PEPCO hatchery. Increased egg production in the rivers or hatchery production of larvae would alter the results of the stipulated model. For instance, stocking 13 million larvae rather than 2.7 million would result in a 4.8 fold increase in biomass of hatchery larvae and juveniles and would result in a 2.4-fold increase in hatchery contribution by stocked larvae to overall (stocked + wild) larval abundance. Alternatively, a large egg production of 7 billion rather than 2 billion in the river would result in a 3.5-fold increase in biomass of wild larvae and juveniles, and result in a 1.3% contribution of 2.7 million stocked larvae. Changing scenarios of initial production rates of wild and hatchery larvae will affect only the relative contribution of hatchery stocked fish. The rates and ontogenetic pattern of biomass accumulation within hatchery and wild cohorts will not be affected.

Patterns of biomass accumulation indicated that under a scenario of low natural egg production, hatchery releases of larvae and juveniles could make >10% contributions to overall abundances (Fig. 7). If larvae were stocked into favorable conditions (intermediate or low mortality rates), then positive rates of biomass increase were expected (Fig. 6). However, under all scenarios, highest biomass accumulation was predicted for hatchery-produced striped bass during the larval stage Therefore, from the perspective of maximizing striped bass production rates, hatchery contribution would be highest if juvenile (Phase I or Phase II) striped bass were stocked.

When costs were factored into hatchery contribution rates, stocking Phase I juveniles was predicted to be most cost effective strategy if 1) Hatchery larval mortality rate was low (Z = 0.025 d^{-1}) and 2) wild larval survival was poor or intermediate (Z = 0.12, 0.20 d^{-1}). However, if hatchery larval mortality rate was high (Z = 0.05 d^{-1}), then stocking larvae was most cost efficient under all scenarios of wild larval survival. In years of high early survival rates of wild larvae, the cost per unit hatchery contribution was 2.5 - 3.3 times lower for released larvae than for released Phase I or Phase II juveniles. Rearing larvae and juveniles under such situations is wasteful because hatchery-pond environments do not increase rates of biomass accumulation over that which would occur in the wild. Because predictions of cost-effectiveness of stocking larvae or Phase I fish was sensitive to estimates of hatchery larval mortality rate, future efforts should be aimed at refining this estimate.

Evaluation of genetic costs of stocking larvae or juveniles, indicated that either strategy was equivalent; effective population size was inversely related to hatchery contribution rate. Secor et al. (1992) reported that single-brood rearing and practices at a South Carolina hatchery resulted in a single female parent contributing 90% of Phase-I juveniles stocked into the Santee-Cooper Reservoir population in 1990. Stocked larvae routinely can be the pooled broods of numerous parents, and can increase genetic representation of stocked fish by lowering the probability that during pond-rearing individual broods will be eliminated either intentionally (i.e. culled) or through disease or other pond-rearing mishaps (Kerby and Harrell 1990). Larval stocking also will limit the capacity of hatchery production relative to natural production so that hatchery contributions will not exceed 90%. At levels greater than 90% contribution, N_E dropped to levels below those recommended for fishery recovery programs ($N_E \leq 424$; Tave 1986).

Larval stocking as a strategy to enhance juvenile production and recruitment of striped bass has other important advantages over juvenile stocking. We believe that stocked larvae will adopt behaviors that lead to successful feeding, growth, and survival in the natural environments into which they are released. Released larvae had similar growth and mortality rates and dispersal patterns compared to contemporary wild cohorts (Secor et al. 1995; 1996). Larvae reared in ponds and stocked as juveniles, may develop behaviors that are favorable in the 'artificial' pond environment but not in juvenile nurseries. For example, Andreasen (1995) found that hatchery-origin Phase II juveniles suffered high predation mortality ($Z = 0.16$ to $0.36\ d^{-1}$) during the first four days after stocking in the Patuxent River, apparently because their behavior promoted cannibalism by older wild striped bass. By the juvenile stage it is probable that fish stocked as larvae and surviving to the juvenile stage will have been "selected" to behave more appropriately in the natural environment, and their survival potential will increase.

Application of Approach to Other Species

Comparisons of ontogenetic patterns of cohort biomass between hatchery and natural environments could provide perspective on the efficiency of stock enhancement strategies in other anadromous and coastal fishes. Salvanes et al. (1994) used a similar approach which considered the ratio Z/G as an index of cohort biomass production to evaluate stocking different age (size) cod juveniles into fjords from pond production. These approaches require accurate estimates of vital rates in natural and artificial environments. Otolith-based aging of larvae and juveniles and larval-mark recapture experiments can provide estimates of vital rates in the field (Tsukamoto 1989; Secor et al. 1995c). However, hatchery based estimates of embryo and larval stage-specific abundances may require better methods than are currently employed.

We believe that comparing stage-specific rates of biomass accumulation may be particularly relevant to American shad (*Alosa sapidissima*), which are similar to striped bass. Shad spawn pelagic eggs in tributaries of estuaries and exhibit high early mortality rates that are largely controlled by environmental factors (Crecco and Savoy 1984). Federal and state hatcheries have been releasing millions of American shad larvae into the Susquehanna River, Chesapeake Bay's largest tributary, since 1976 (St. Pierre 1994) and other state and federal agencies are rapidly developing and expanding larval stocking programs elsewhere in the Chesapeake Bay region (Garman 1995). Despite these enhancement programs, little is known of larval and juvenile production rates in the wild (Kahn and Weinrich 1994), and the efficiency of hatchery production relative to natural production remains unevaluated.

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Table 1. Striped bass larval mark-recapture experiments, Patuxent River (1991) and Nanticoke River (1992-1993. Release records for striped bass larvae by year. Broods are designated according to Maryland Department of Natural Resources Hatchery records. Release site indicates batches of larvae which were released at downriver and upriver sites within the striped bass nursery. "Ages marked" indicate the ages at which larvae were immersed in 25 ppm alizarin complexone or 400 ppm tetracycline hydrochloride for 6 hr to mark their otoliths. Numbers released were estimated volumetrically (i.e. number m^{-3}) in rearing troughs 6 hr before release.

Brood(s)	Larval Release Date	Release Site	Age at Release (d)	Ages Marked (d)	Millions Released
1991 - Patuxent River					
P-8	26 April	Downriver	9	0	0.72
P-9, 10, 11, 12, 13	26 April	Upriver, Downriver	9	8	3.24
P-12,13	30 April	Upriver, Downriver	13	6	1.44
P-14, 16, 17, 18	30 April	Upriver, Downriver	9	2	1.14
Total Released					6.54
1992 - Nanticoke River					
N-13	24 April	Downriver	8	7	0.65
N-13	24 April	Upriver	8	5	1.13
N-15, 17, 20	25 April	Downriver	5	1, 3	1.55
N-14, 16	25 April	Upriver	5	1	0.93
N-15, 17, 20	28 April	Downriver	8	1, 3, 6	1.72
N-14, 16	28 April	Upriver	8	1, 6	2.72
N-18, 21	1 May	Downriver	10	0, 7	2.40
N-19, 22	1 May	Upriver	10	0, 9	2.12
Total Released					13.22
1993 - Nanticoke River					
N-1, N-3, N-4	21 April	Upriver, Downriver	10	8	2.18
N-5, N-7	25 April	Upriver, Downriver	12	8	1.07
N-11, N-13	25 April	Upriver, Downriver	9	5	2.48
N-16, N-17, N-18	29 April	Upriver, Downriver	6	4	3.98
N-19, N-20	3 May	Upriver, Downriver	6	4	2.18
Total Released					11.89
1991 - 1993					
Total Released					31.65

Table 2. Striped bass larval mark-recapture experiments, Patuxent River (1991) and Nanticoke River (1992-1993. Growth and mortality coefficients among hatchery-produced release groups. g = length-specific growth coefficient; G = weight-specific growth coefficient. G coefficient was based upon converted lengths using a weight-length relationship (Houde and Lubbers 1986). Release site indicates batches of larvae which were released at downriver and upriver sites within the striped bass nursery.

Release Date	Release RK	Age at Release	g ± S.E. (d^{-1})	G (d^{-1})	Z ± S.E.
26 April	Up, Down	9	0.037 ± 0.003	0.157	0.154 ± 0.049
26 April	Up, Down	9	0.032 ± 0.001	0.139	0.085 ± 0.039
30 April	Up, Down	13	0.036 ± 0.008	0.153	0.188 ± 0.084
26 - 30 April	Up, Down	9-13	0.032 ± 0.001	0.139	---
1992 - Nanticoke River					
24 April	Up	8	0.007 ± 0.0033	0.028	0.159 ± 0.038
24 April	Down	8	0.028 ± 0.0028	0.121	0.091 ± 0.024
25 April	Up	5	0.031 ± 0.0023	0.133	0.103 ± 0.032
25 April	Down	5	0.025 ± 0.0024	0.106	0.075 ± 0.022
28 April	Up	8	0.014 ± 0.0017	0.061	0.145 ± 0.118
28 April	Down	8	0.028 ± 0.0030	0.118	0.149 ± 0.021
1 May	Up	10	0.025 ± 0.0038	0.106	0.135 ± 0.051
1 May	Down	10	---	---	0.161 ± 0.399
24 April	Up, Down	8	0.026 ± 0.0028	0.109	0.111 ± 0.025
25 April	Up, Down	5	0.027 ± 0.0020	0.114	0.082 ± 0.027
28 April	Up, Down	8	0.026 ± 0.0030	0.113	0.162 ± 0.025
1 May	Up, Down	10	0.024 ± 0.0036	0.105	0.148 ± 0.055
24 Apr - 1May	Up, Down	5 - 10	0.026 ± 0.0013	0.111	---
1993 - Nanticoke River					
21 April	Up, Down	10	---	---	---
25 April	Up, Down	9	0.035 ± 0.0029	0.153	0.066 ± 0.017
25 April	Up, Down	12	0.034 ± 0.0023	0.147	0.108 ± 0.021
29 April	Up, Down	6	0.030 ± 0.0022	0.128	0.047 ± 0.032
3 May	Up, Down	6	0.030 ± 0.001	0.130	0.039 ± 0.009
21 Apr - 3 May	Up, Down	6 - 12	0.032 ± 0.0015	0.136	---

Table 3. Striped bass larval mark-recapture experiments, Patuxent River (1991) and Nanticoke River (1992-1993. Petersen population estimates for juveniles on 14 July 1992 and 13 July 1993. Total wild population estimate from Minkkinen (1993) and Minkkinen (pers. comm.) does not include hatchery-stocked juveniles with coded wire tags. N = number of recaptured juveniles that originated from release of hatchery-produced larvae.

Release Date	Release Site (RK)	N	Petersen Estimate	95% Confidence Intervals	Survival (%)
			1991 - Patuxent		
26 April	Up-,Downriver	5	22,184	5,385 - 39,381	0.68
1 May	Up-,Downriver	2	8,874	387 - 18,849	0.78
All Releases	Up-,Downriver	7	31,058	9,425 - 48,469	0.48
Total Wild			110,922		
Released % Contribution			23.5%		
			1992 - Nanticoke		
24 April	Upriver	0	0	—	0.0
24 April	Downriver	0	0	—	0.0
25 April	Upriver	4	15,025	2,682 - 55,428	0.97
25 April	Downriver	8	30,050	9,068 - 85,824	3.23
28 April	Upriver	3	11,269	1,660 - 47,765	0.65
28 April	Downriver	14	52,588	20,689 - 127,714	1.93
1 May	Upriver	5	18,781	4,342 - 63,601	0.78
1 May	Downriver	0	0	—	0.0
All Releases	Up-,Downriver	34	127,714	88,273 - 178,424	0.97
Total Wild			315,528		
Released % Contribution			28.8%		
			1993 - Nanticoke		
25 April (12-d larvae)	Up-,Downriver	2	120,809	12,081 - 434,913	11.29
All Releases	Up-,Downriver	8	483,237	205,376 - 954,392	4.06
Total Wild			9,132,141		
Released % Contribution			5.3%		

able 4. Striped bass stocking biomass model. Estimates of stage-specific mortality and growth rates and masses used tc odel biomass in hatchery and naturally produced striped bass. Pax-91 = Patuxent River 1991, Nan-92 = Nanticoke River 992, Nan-93 = Nanticoke River 1993, PEPCO = Potomac Electric Power Company Aquaculture Program, SC = South arolina Department of Natural Resources hatchery (Secor et al. 1992), CBL = Chesapeake Biological Laboratory, Wild = ooled data from 1991-1993 ichthyoplankton surveys; Hatch = pooled data from PEPCO, SC, and CBL. Z_1 = embryo ortality rate, Z_2 = larval mortality rate, Z_3 = juvenile mortality rate, G_1 = embryo growth rate, G_2 = larval growth rate, $_3$ = juvenile growth rate, Wt_1 = larval weight at 7 days posthatch (mg), Wt_2 = juvenile wet weight at 55 days posthatch. Vt_3 = juvenile wet weight at 220 days posthatch. Values shaded are those used in the biomass model.

	Z_1 (d^{-1})			Z_2 (d^{-1})			Z_3 (d^{-1})		
Source	mean ± s.e	median	n	mean ± s.e	median	n	mean ± s.e	median	n
Pax-91	0.348	-	1	0.226 ± 0.079	0.149	8	0.012	-	1
Nan-92	0.706	-	1	0.191 ± 0.037	0.182	7	0.005	-	1
Nan-93	0.690	-	1	0.125 ± 0.018	0.131	8	0.021	-	1
PEPC	-	-	-	0.025 ± 0.003	0.017	61	0.002 ± ?	?	8
SC	0.155 ± 0.026	-	3	0.039 ± 0.009	0.020	12	-	-	-
Wild	0.581 ± 0.117	-	3	0.183 ± 0.031	0.141	23	0.013 ± 0.005	-	3
Hatch	0.155 ± 0.026	-	3	0.025 ± 0.003	0.017	73	0.002	-	8
	G_1 (d^{-1})			G_2 (d^{-1})			G_3 (d^{-1})		
Pax-91	-	-	-	0.126 ± 0.005	0.126	7	0.020	-	1
Nan-92	-	-	-	0.165 ± 0.011	0.171	8	0.021	-	1
Nan-93	-	-	-	0.159 ± 0.009	0.159	9	0.023	-	1
PEPCO	-	-	-	0.190 ± 0.003	0.188	62	0.025 ± 0.0001	0.025	24
Wild	-	-	-	0.151 ± 0.006	0.146	24	0.021 ± 0.0001	-	3
Hatc	-	-	-	0.190 ± 0.003	0.188	62	0.025 ± 0.0001	0.025	24
	Wt_1 (mg)			Wt_2 (mg)			Wt_3 (mg)		
Pax-91	0.582 ± 0.069	0.611	6	184.58 ± 68.91	102.71	7	10250.5	-	-
Nan-92	0.725 ± 0.027	0.705	8	787.81 ± 280.18	350.80	7	10205.5	-	-
Nan-93	0.630 ± 0.053	0.651	9	675.57 ± 249.92	275.26	9	10205.5	-	-
PEPCO	-	-	-	370.67 ± 54.25	332.09	24	24783.30 ± 1917.45	23785.90	24
CBL	0.586 ± 0.169	-	2	-	-	-	-	-	-
Wild	0.650 ± 0.030	0.673	23	560.30 ± 136.76	275.26	23	10205.5	-	1
Hatch	0.586 ± 0.169	-	2	370.67 ± 54.25	332.09	24	24783.30 ± 1917.45	23785.90	24

Table 5. Striped bass stocking biomass model. Estimates of changes of variance in family size (V_K) and effective number of spawners (N_E) associated with variance in survival to 7 or 55 days after hatch under the scenario of egg productions of 5 or 10,000 female spawners in the hatchery and wild, respectively.

Source	Age	V_K	N_E
Hatchery	0	0	5.0
	7	4.00	3.3
	55	6.22	2.8
Wild	0	0	10000
	7	5.93	5044
	55	6.05	4969

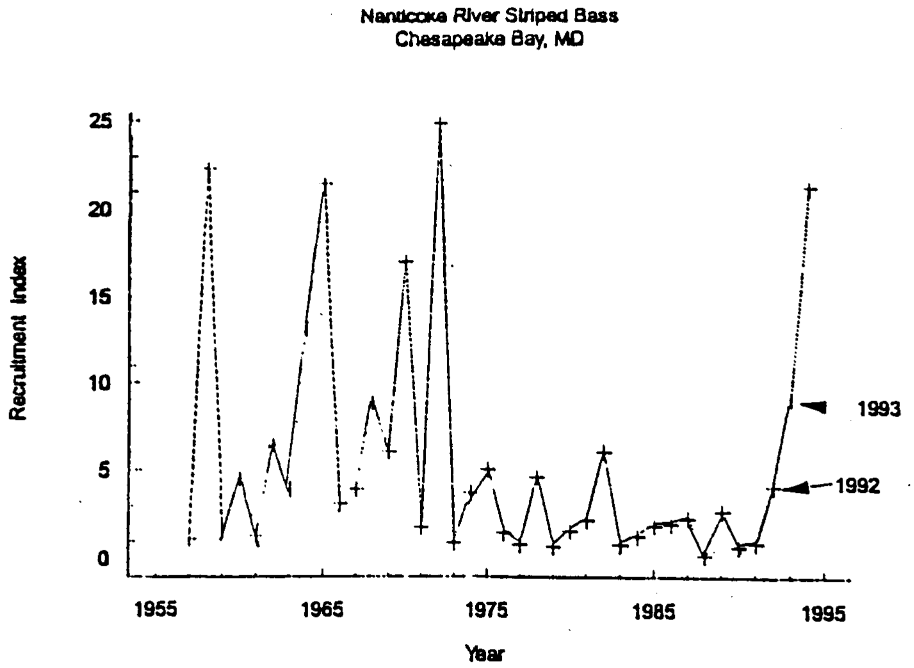

Figure 1. Striped bass recruitment time series for the Nanticoke River (Chesapeake Bay), 1956-1994. Recruitment is indexed by young-of-the-year abundance measured as the mean number of juveniles collected in seine surveys of the Nanticoke River (Cosden and Barbour 1995).

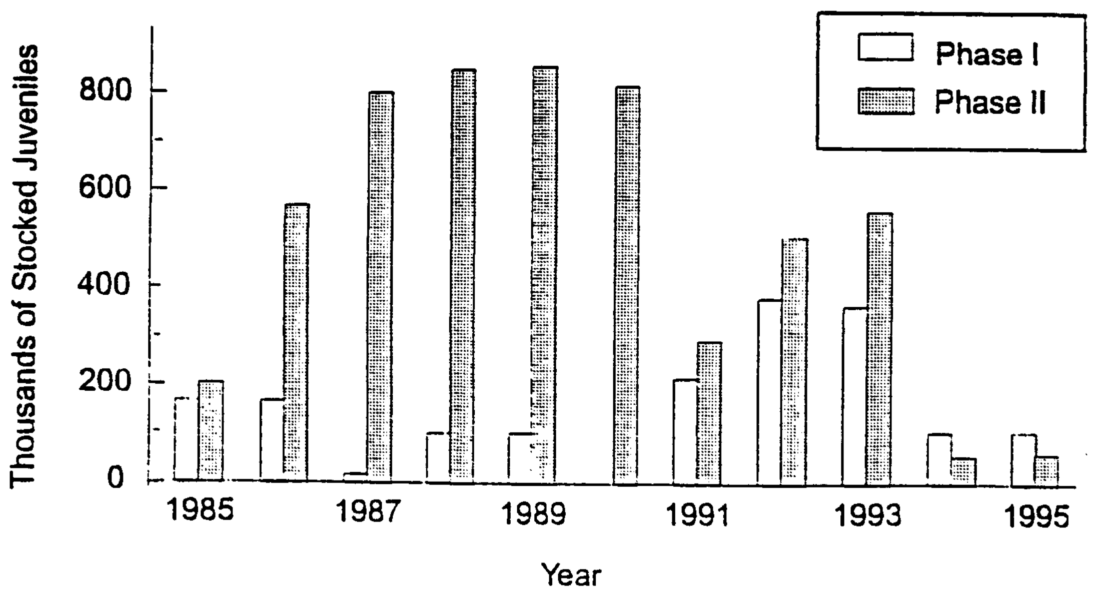

Figure 2. Numbers of Phase I (35 - 50 mm TL) and Phase II (150 - 200 mm TL) striped bass juveniles stocked into Maryland, Chesapeake Bay tributaries as part of the striped bass restoration program, 1985-1995.

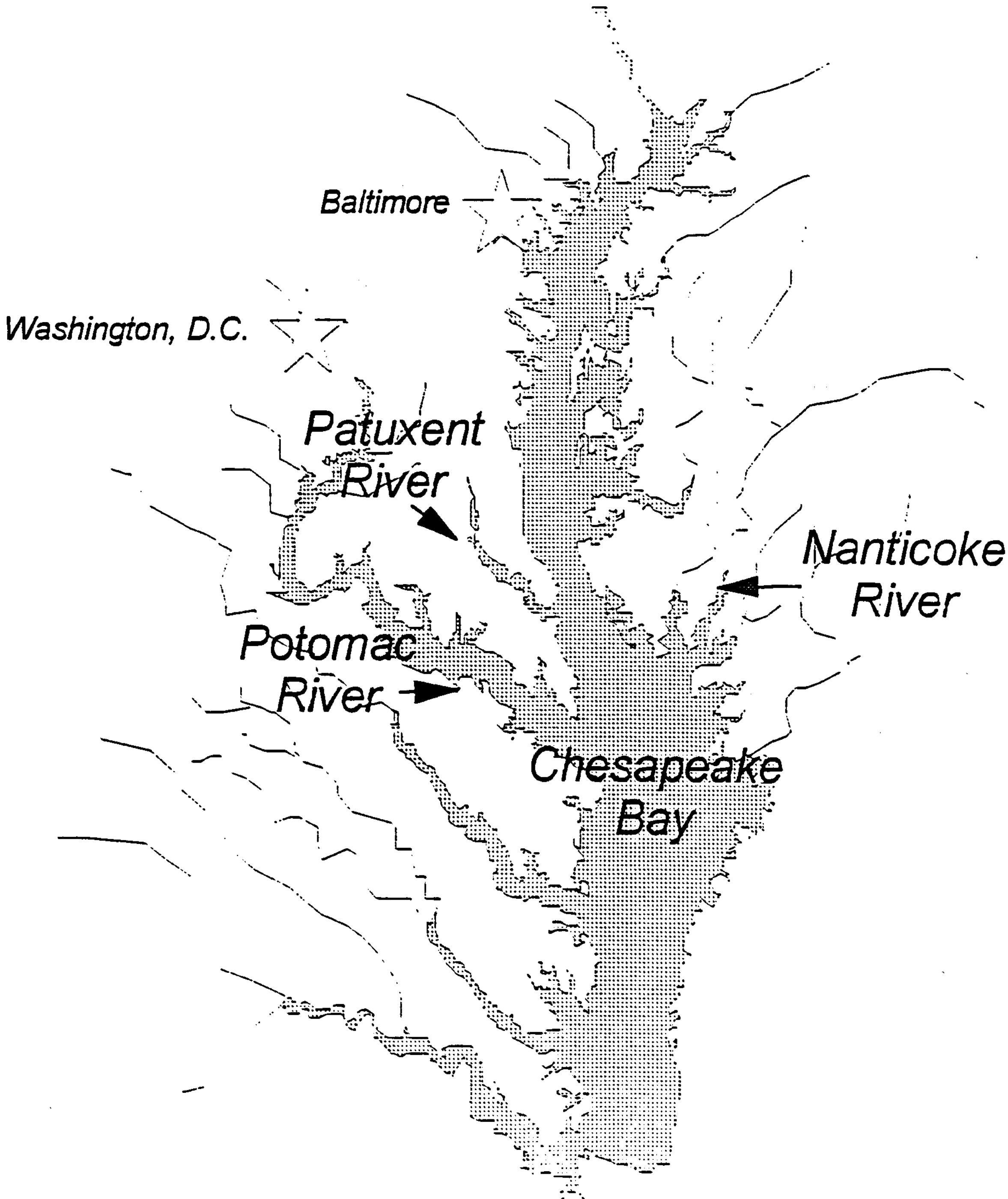

Figure 3. Map of Chesapeake Bay showing Patuxent and Nanticoke Rivers.

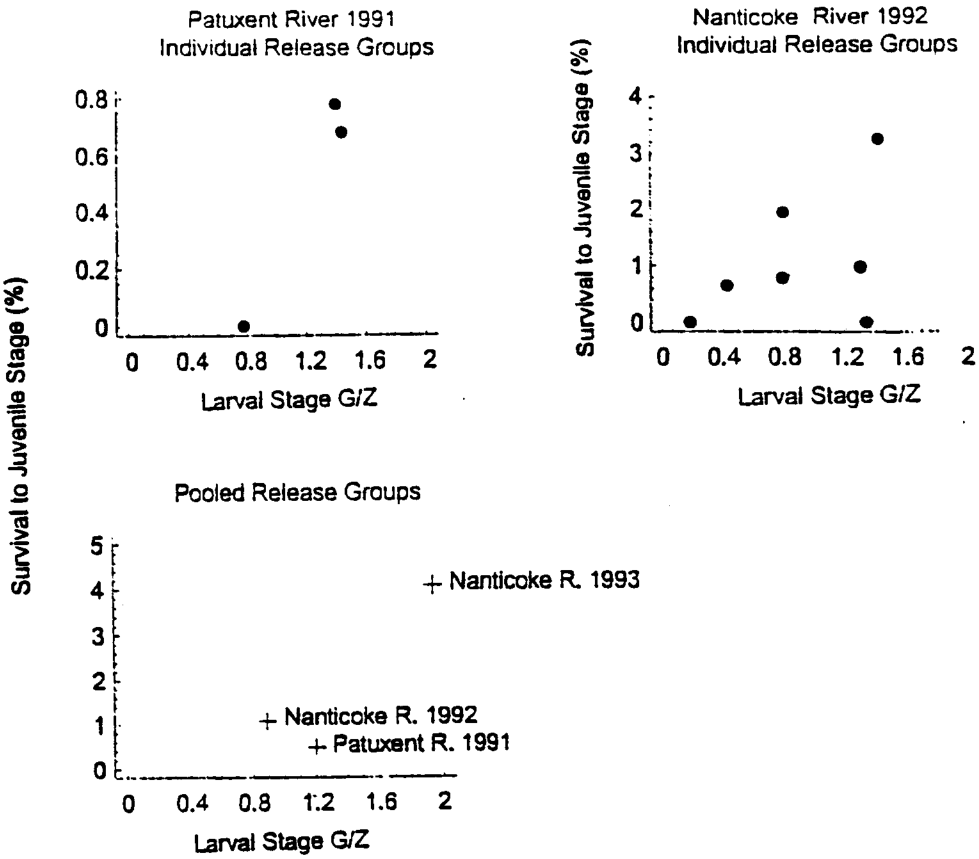

Figure 4. Plots of overall survival of released striped bass larvae to the juvenile stage (mid-July) versus larval stage G/Z ratio for larval releases in the Patuxent River (1991) and Nanticoke River (1992). In the bottom plot, overall survival was pooled among release groups for each year and plotted against larval G/Z ratio.

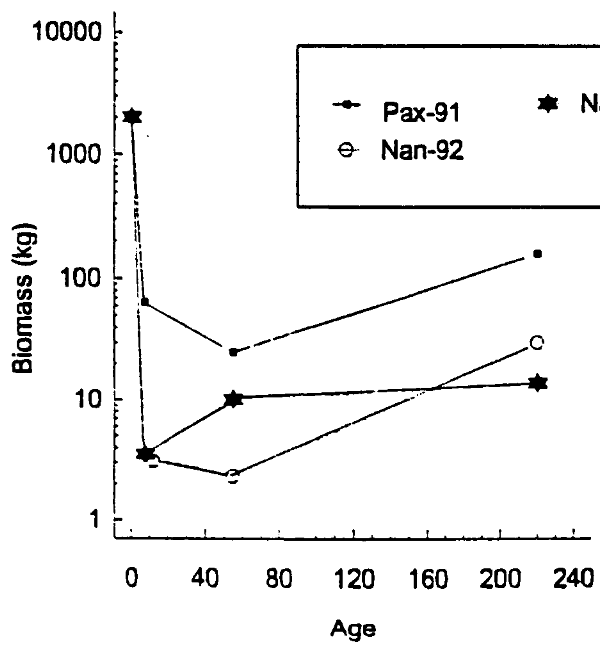

Figure 5. Ontogenetic changes in striped bass cohort biomass for wild larvae and juveniles in the Patuxent (1991) and Nanticoke (1992, 1993) Rivers. Note that for the purpose of comparison, initial cohort biomass was specified at 2000 kg, despite observed differences in egg productions among years. Data used to determine annual cohort biomasses are presented in Table 4.

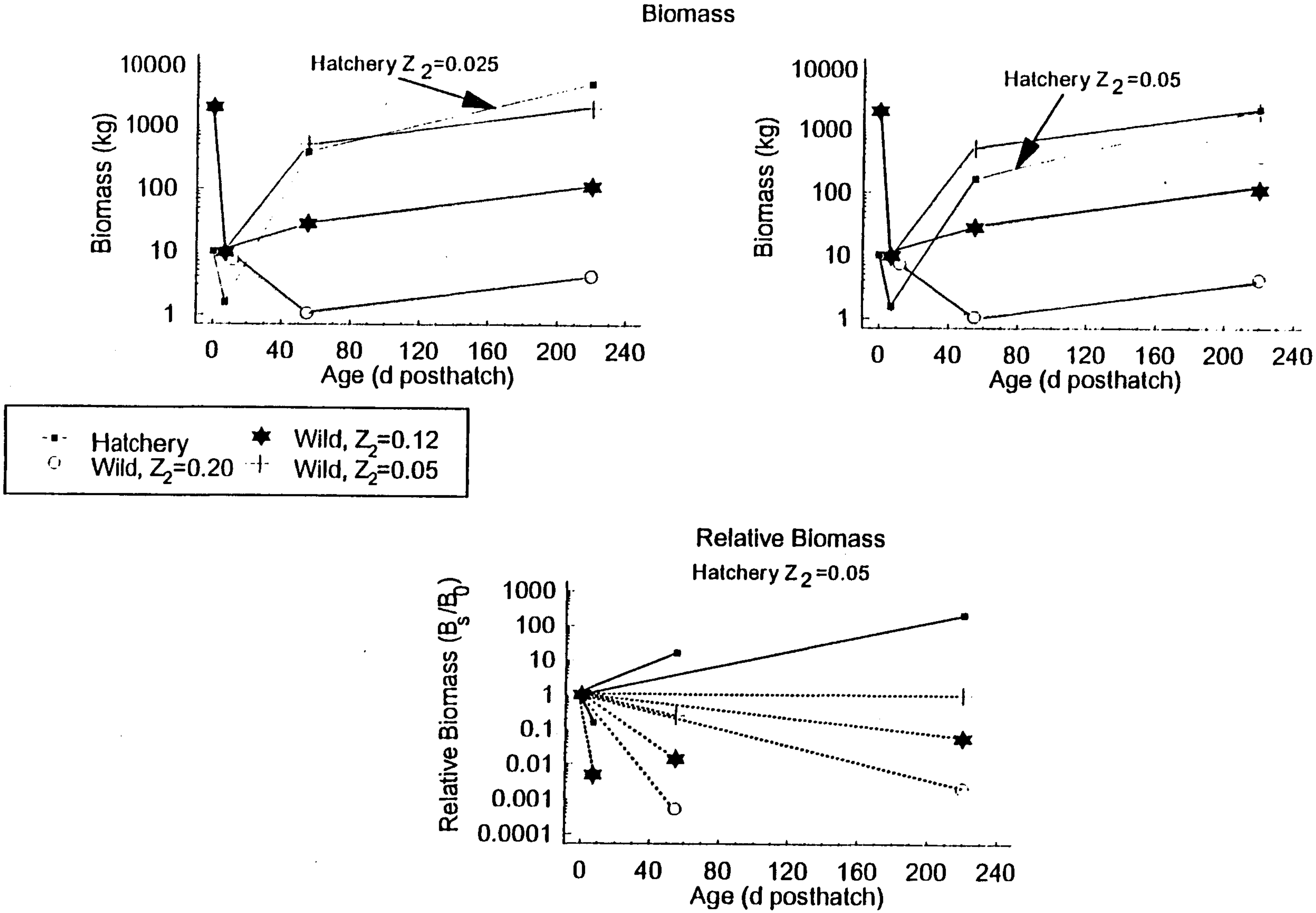

Figure 6. Ontogenetic changes in striped bass cohort biomass for wild and hatchery larvae and juveniles. In the two upper plots, hatchery larval stage mortality is specified at low ($Z_2 = 0.025\ d^{-1}$) or high ($Z_2 = 0.05\ d^{-1}$) levels. Within each plot, three levels of wild larval-stage mortality are specified. The lower plot shows biomass relative to initial biomass (B_S/B_0) at the higher hatchery larval mortality rate. A plot of relative biomass at the lower hatchery mortality rate (not shown) indicated the same trends in biomass relative to age.

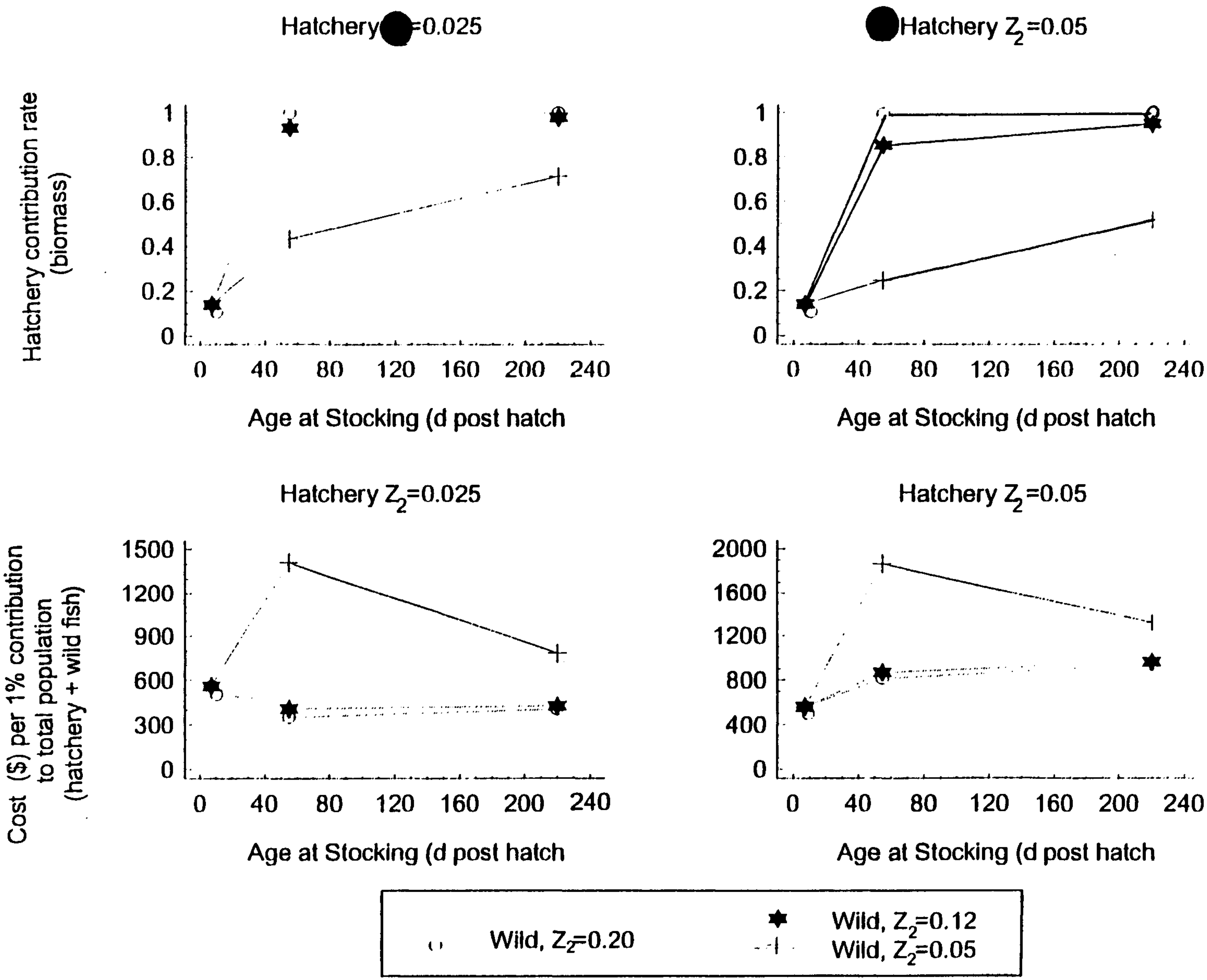

Figure 7. Hatchery contribution rates (hatchery biomass/(hatchery + wild biomass)) of striped bass stocked at 7, 55, or 220 days after hatch. The two lower plots show the cost of contributing 1% to the overall biomass (wild + hatchery) of striped bass stocked at 7, 55, or 220 days after hatch. Scenarios of wild and hatchery larval mortality rates are shown.