SURVIVAL AND CONTRIBUTION OF HATCHERY-REARED STRIPED BASS STOCKED IN THE SACRAMENTO-SAN JOAQUIN ESTUARY

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ABSTRACT

The abundance of striped bass *Morone saxatilis* in the Sacramento-San Joaquin Estuary has been declining since the 1970s. The California Department of Fish and Game started a stocking program in 1981 to help restore the population. An associated hatchery evaluation program monitors the survival and contribution to the fishery of the stocked fish. Results showed that (i) the percentage of the population formed by hatchery fish increased as the number of fish stocked increased, reaching a maximum of 35% for the 1990 year class; (ii) estimated survival to age 3 for stocked yearlings decreased as the number stocked increased; (iii) hatchery-reared striped bass that were older and larger at release survived better than younger and smaller fish. Our results indicate that maximum survival to recruitment and contribution to the fishery is obtained by stocking large yearling striped bass in San Pablo Bay.

Striped bass *Morone saxatilis* were first introduced into California's Sacramento-San Joaquin Estuary in 1879 (Scofield and Bryant 1926, Craig 1928, Skinner 1962). Two groups of fish were planted in the Carquinez Strait–Suisun Bay area: 132 fish from the Navesink River, New Jersey and 300 fish from the Shrewsbury River, New Jersey. By 1899, the well-established commercial fishery reported annual striped bass catches greater than 450,000 kg. Recreational fishing for striped bass also became popular, co-existing with the commercial striped bass fishery until 1935, when legislation eliminated the commercial fishery.

Legal-sized (40.6 cm total length [TL] before 1982, 45.7 cm TL from 1982 to present) striped bass abundance has been monitored since 1969 using mark-recapture techniques (Stevens 1977). From 1969 to 1976, the number of legal-sized striped bass was relatively stable, ranging from 1.5 to 1.9 million fish (Stevens et al. 1985). Since 1976, abundance declined to 800,000–1.2 million fish in the late 1970s and 1980s and 579,000 legal-sized fish in 1994 (Figure 1). Possible causes for the decline include entrainment losses at water diversions, inadequate food supply for young bass, lack of adequate egg production, and impact of toxicants on adults and juveniles (Stevens et al. 1985).

As a result of the decline in striped bass abundance and in response to public pressure the California Department of Fish and Game (CDFG) began a hatchery stocking program in 1981. The number of fish stocked increased from about 63,000 yearlings in 1981 to almost 3.4 million for the 1990 year class (Table 1). This increase was due mostly to the purchase of large numbers of fish from private aquaculturists by the Pacific Gas and Electric Company (PG&E) and the California Department of Water Resources (CDWR) as

mitigation for young striped bass lost to impingement and entrainment.

Stocking of hatchery-reared fish was suspended after the 1990 year class because of concern over potential predation by striped bass on the endangered Sacramento River winter-run chinook salmon *Oncorhynchus tshawytscha*. Beginning with the 1992 year class, 22,000–284,000 fish were obtained annually from fish screens in the south Sacramento-San Joaquin Delta, reared in net pens, and stocked as yearlings in the estuary.

California's striped bass stocking program is different from hatchery programs elsewhere because it has emphasized stocking age-1 fish (about 150–320 mm TL). Hatchery programs on the east (Dorazio et al. 1991, Wooley et al. 1990, Van den Avyle et al. 1995) and Gulf (Lukens et al. 1991, Nicholson 1996) coasts have supplemented wild populations with "phase-I" (15–80 mm TL) and "phase-II" (150–250 mm TL) fingerlings released in summer and fall of their first year of life.

The CDFG began evaluating the effectiveness of stocking hatchery-reared striped bass in 1982. The CDFG hatchery evaluation study samples the proportion of hatchery fish in the population when they are recruited to the sport fishery at 45.7 cm TL, usually at age 3. Hatchery evaluations elsewhere using marked fish have commonly estimated contribution to the wild population from the proportion of hatchery fish in samples of juveniles in their 1st year of life (e.g., Dorazio et al. 1991, Lukens et al. 1991, Minkkinen et al. 1995), although one study examined relative survival rates at ages ≥ 1 (Wallin and Van den Avyle 1995a), and others have sampled the commercial and sport fisheries (USDI and USDC 1995, Waldman and Vecchio 1996).

In this paper, we evaluate the effectiveness of this effort by (1) estimating the

contribution of hatchery-reared striped bass to the exploitable population in the Sacramento-San Joaquin Estuary, (2) survival of hatchery-reared striped bass, and (3) suggest an optimal stocking protocol.

The study area includes the lower Sacramento-San Joaquin rivers, their common delta, San Pablo Bay, San Francisco Bay, and the ocean inshore-area north to Tomales Bay and south to Morro Bay [could possibly use Half Moon or Monterey Bay here] (Figure #, maybe a less detailed version of the map that Mary Sommer prepared) ---- this is from the S.B. management plan Phase I intro.

METHODS

Over 11 million juvenile striped bass were stocked in the Sacramento-San Joaquin Estuary from 1981-1990; more than 5.3 million were marked (Table 1). Hatchery-reared juvenile striped bass were the first-generation progeny of wild brood stock, collected annually by electrofishing in the Sacramento and San Joaquin rivers and taken to hatcheries for spawning (Cochran 1992). In 1980-1982, all fish were raised at CVH; from 1983 to 1991, several private aquaculture facilities were contracted to also raise striped bass. All hatcheries used the traditional "extensive" or pond culture method (Anderson 1966, Bonn et al. 1976, Stevens 1979).

The only other juvenile striped bass stocked into the study area were collected from fish screens of the John E. Skinner Fish Facility (Fish Facility) at the intake to the California Aqueduct. From 1984 to 1991, striped bass collected at the Fish Facility were reared at CDFG facilities. In 1990 and 1991, striped bass collected at the Fish Facility also

were reared by private aquaculturists. Since 1992, striped bass collected at the Fish Facility have been reared in floating net pens located, at various times, in the brackish-water channels of the Suisun and Napa marshes and in San Francisco Bay.

Three types of marks have been used to identify hatchery-reared striped bass. Prior to 1984, fish were marked by freeze branding and pelvic fin excision (fin clips). Since 1984, coded-wire tags (magnetized stainless-steel microtags, CWTs) have been implanted into the left adductor mandibularis (cheek muscle). In 1986 and 1989, subgroups of fish were marked with freeze brands, fin clips, and CWTs to assess the loss rate of each mark.

Marked hatchery-reared striped bass were recovered by sampling the sport fishery with a creel census and by sampling during the spring spawning season with gill nets and fyke traps in the western Sacramento-San Joaquin Delta and Sacramento River (Stevens 1977). Striped bass observed during these sampling programs were visually inspected for freeze brands and fin clips. The presence of a CWT was determined using a tube or wand type detector. When a CWT was present, cheek muscles were excised to recover the CWT.

Fork length, recapture location, and recapture date were recorded for all fish examined for marks. Scales were collected for age determination. These data were used to estimate the age and size distributions of striped bass observed during collection efforts. In combination with data from legal-sized fish marked with disk-dangler tags (Chadwick

1963), these data were also used to estimate cohort abundance and mortality rates of legal-sized striped bass (Stevens 1977).

An index of the contribution of hatchery-reared fish in each year class was calculated by dividing the number of hatchery-marked striped bass recovered by the total number in the recovery sample. The contribution was estimated for each age (3–7). Most fish less than age 3 were not legal-sized (≧ 45.7 cm TL), and fish older than age 7 could not be reliably aged with scales.

The number of hatchery-marked striped bass recovered was adjusted by correcting observed recoveries for the fraction of the year class not marked and the mark loss/non-detection rate. The first correction factor was the quotient of the total number of fish stocked (tagged and untagged) and the number of fish stocked that were tagged. The correction factors for mark loss/non-detection (CWTs: 1.03; freeze brands and fin clips: 1.14) were calculated as the reciprocal of the shedding rate determined from results of double-marking experiments in 1986 and 1989 (CDFG, unpublished data). The adjusted number of hatchery-marked striped bass was estimated annually for each year class as the product of the number of observed marked fish and the two correction factors.

Estimated Survival to Recruitment

Survival to recruitment into the legal-sized population was estimated as the quotient

of estimated abundance of surviving hatchery-reared fish at age 3 and the total number of hatchery fish originally released. Estimated abundance of surviving hatchery-reared fish was the product of the mark-recapture estimate of age 3 abundance and the fraction of the year class that are hatchery fish (mean of estimated fraction at ages 3–7).

Experimental Stocking Studies

For these studies, we used recovery rate (estimated number of hatchery-reared striped bass recovered in the creel census, gill nets, and fyke traps divided by the number of fish stocked) as a surrogate for survival rate. Recoveries were accumulated over all ages at which a release group was sampled. Statistical significance of differences in recovery rates between release groups was tested using chi-square contingency tables comparing marks recovered and not recovered among release groups.

The effect of age at stocking on survival to recruitment was investigated by stocking juvenile striped bass as fingerlings, advanced fingerlings, and yearlings. Fingerlings and advanced fingerlings were stocked in November of the year of hatching at the age of 6–7 months. Yearlings were stocked in May or June of the year following hatching at about 1 year of age.

The effect of size at stocking on survival to recruitment was examined for both yearlings and fingerlings. Yearlings were grouped into three size categories: small, medium, and large. Small yearlings weighed less than 45 g, medium yearlings weighed 45–90 g, and large yearlings weighed 91–450 g. Fingerlings were grouped into two size categories: fingerlings and advanced fingerlings. Fingerlings weighed 12–25 g and advanced fingerlings were the size of medium-sized yearlings (about 65 g). Advanced fingerlings grew rapidly because they were reared in warm water (24–27°C).

Because of differences in such factors as salinity, turbidity, and predator and prey abundance, stocking location may affect survival to recruitment. To test for effects of stocking location, hatchery-reared striped bass were stocked in the Sacramento and San Joaquin rivers (low salinity, high turbidity) and in San Pablo Bay (brackish water, low turbidity). The effect of stocking location on survival was examined for fingerlings and advanced fingerlings and for yearlings of hatchery and wild (Fish Facility) origin.

The effect of origin of yearling hatchery-reared striped bass on survival to recruitment was evaluated using fish that were spawned and reared in hatcheries (hatchery-spawned) or collected at the Fish Facility and then reared in hatcheries (wild-spawned). Separate comparisons were made for fish stocked in San Pablo Bay and in the Sacramento River.

We estimated the cost of putting a hatchery-reared striped bass in the legal-sized population by dividing the mean cost per stocked fish in 1986 and 1987 (years when all three sizes of hatchery fish were purchased) by the mean survival rate to age 3. Mean cost per stocked fish was US$0.72 for fingerlings, $1.41 for advanced fingerlings, and $1.55 for yearlings (CDFG, unpublished data).

RESULTS

Contribution of Hatchery-Reared Striped Bass to the Population

Estimated percentage of hatchery-reared striped bass in the population has increased since sampling began in 1984, from about 1% for the 1981 year class to almost 35% for the 1990 year class (Figure 2). The fractional contribution of hatchery-reared striped bass to each year class was linearly related to stocking rate (r^2 = 0.88, $P < 0.001$) (Figure 3).

Estimated Survival to Recruitment

Estimated survival to recruitment at age 3 for hatchery-reared yearling striped bass varied from 0.041 for the 1990 year class to 0.175 for the 1982 year class; mean survival

was 0.098 (Table 2). Survival of hatchery-reared yearlings decreased nonlinearly as the number of fish stocked increased (r^2 = 0.49, *P* <0.05) (Figure 4).

Fish smaller and younger than yearlings at the time of stocking had lower survival than yearlings. Survival of fingerlings ranged from 0.004 for the 1990 year class to 0.013 for the 1989 year class; mean survival was 0.009 (Table 2). Advanced fingerlings were only stocked in 3 years (1985–1987) and mean survival was 0.022.

Experimental Stocking Studies

Study design and the necessities of hatchery management often prevented inclusion of all hatchery-reared marked striped bass in our analyses. Frequently, differences in size of stocked fish or other variables prevented valid inferences from statistical tests. As examples, fish stocked at one location may have been larger than those stocked at another location, making it impossible to compare survival of similar fish between locations; fish may have differed in size at the same age, making it impossible to compare survival between ages; or some wild- and hatchery-spawned yearlings could not be compared because they also differed in size. Therefore, comparisons involving all variables were not possible for all years or locations, even though the experiments were done, and some year classes or size groups are missing from the following comparisons. Cumulative recovery rates for more recent year classes are generally lower than for earlier year classes, which had more recovery years.

Effect of Age at Stocking on Survival to Recruitment

In all cases, irrespective of year or stocking location, hatchery-reared yearling striped bass were recovered at a significantly higher rate than fish that were younger at release (χ^2 tests, all $P < 0.001$). Yearling recovery rate (and, hence, survival) ranged from 2 times better than fingerling survival for the 1988 year class released in the Sacramento River (Figure 5a) to 20 times better for the 1990 year class released in San Pablo Bay (Figure 5b). Overall, for Sacramento River releases, yearlings were recovered at a rate about 4 times that of fingerlings. For San Pablo Bay releases, yearlings were recovered at a rate 8 times higher than fingerlings.

Differences between recovery rates for yearlings and advanced fingerlings also favored older fish (χ^2 tests, all $P < 0.001$). They ranged from yearling recovery rates 2 times greater than that of advanced fingerlings for the 1987 year class stocked in both San Pablo Bay and the Sacramento River (Figure 6) to 16 times greater for the 1985 year class stocked in San Pablo Bay (Figure 6b). On average, for Sacramento River releases, yearlings were recovered at >3 times the rate of advanced fingerlings. For San Pablo Bay releases, yearlings were recovered at a rate >4 times that of advanced fingerlings.

Effect of Size at Stocking on Survival to Recruitment

Marked hatchery-reared striped bass of the same age that were larger when stocked were recovered at higher rates than smaller fish. Larger (advanced) fingerlings (about 65

g) were recovered at a significantly higher rate than smaller fingerlings (12–25 g) in both years when they were released simultaneously (1986: $\chi^2 = 97.4$, $P < 0.001$; 1987: $\chi^2 = 37.9$, $P < 0.001$) (Figure 7). Overall, advanced fingerlings were recovered at almost 4 times the rate of fingerlings.

In individual years, except for 1987, and for all years combined, hatchery-reared yearling striped bass that were larger at stocking were recovered at significantly higher rates than fish that were smaller at release (χ^2 tests, $P < 0.001$) (Figure 8). In the exceptional year 1987, comparisons with large yearlings were confounded by other variables and recovery rates for small (<45 g) and medium (45–90 g) yearlings were not significantly different ($\chi^2 = 0.15$, $P = 0.70$). Overall, large yearlings (>90 g) survived to recruitment about 3 times better than medium-sized yearlings and about 6 times better than small yearlings.

Effect of Stocking Location on Survival to Recruitment

The effect of stocking location on survival to recruitment was inconsistent among sizes and ages of stocked fish and varied annually even within size and age groups. Recovery rate for fingerlings released in the Sacramento River was significantly greater (4 times) than for those released in San Pablo Bay in 1989 ($\chi^2 = 12.0$, $P < 0.001$), but not in 1988 ($\chi^2 = 0.13$, $P = 0.72$) or 1990 ($\chi^2 = 1.16$, $P = 0.28$) (Figure 9a). The high recovery rate of fingerlings released in the Sacramento River in 1989 also caused the recovery rate for all 3 years combined to be significantly higher for Sacramento River releases than for San Pablo

Bay releases ($\chi^2 = 13.8$, P < 0..001).

In contrast, recovery rate of advanced fingerlings stocked in San Pablo Bay was significantly higher than for fish stocked in the Sacramento River in 1985 ($\chi^2 = 4.13$, $P < 0.05$), but differences were not significant in 1986 ($\chi^2 = 0.54$, $P = 0.46$) or 1987 ($\chi^2 = 0.74$, $P = 0.39$) (Figure 9b). For all years combined, advanced fingerling recovery rates did not differ between release areas ($\chi^2 = 0.84$, $P = 0.36$).

Two comparisons between stocking locations for yearlings were valid. Yearlings were recovered at a significantly higher rate when released in San Pablo Bay rather than the Sacramento River in 3 of 7 years (1983, 1988, 1990) (χ^2 tests, $P < 0.05$); recovery rate for fish released in the Sacramento River was significantly higher in 1987 ($\chi^2 = 7.31$, P < 0.01). Overall, the recovery rate of yearlings stocked in San Pablo Bay (0.00245) was significantly higher than for yearlings stocked in the Sacramento River (0.00212) ($\chi^2 = 18.9$, $P < 0.001$) (Figure 9c). The recovery rate for yearlings released in the Sacramento River (0.00301) was significantly greater than for those released in the San Joaquin River (0.00219) in 1985 ($\chi^2 = 18.9$, $P < 0.001$), the only year for which such a comparison was possible. Confounding of release location with other variables invalidated comparisons between yearlings released in San Pablo Bay and the San Joaquin River.

Comparisons of the effect of stocking location on recovery rates for yearlings stratified according to whether they were spawned in a hatchery or in the wild also suggested that stocking location had an inconsistent effect on survival. Survival of hatchery-spawned fish stocked in San Pablo Bay was significantly better than for those stocked in the Sacramento River for 2 of 5 year classes (1983: $\chi^2 = 118.5$, $P < 0.001$; 1990:

(χ^2 = 5.24, *P* < 0.05), but better in the Sacramento River in 1987 (χ^2 = 7.31, *P* < 0.01). Overall, for hatchery-spawned yearlings, survival was significantly better for fish released in San Pablo Bay than for those released in the Sacramento River (χ^2 = 15.0, *P* < 0.001) (Figure 10a). Recovery rates of wild-spawned yearlings stocked in San Pablo Bay and the Sacramento River were not significantly different for any year class or overall (χ^2 tests, *P* > 0.10) (Figure 10b).

Effect of Origin of Fish on Survival to Recruitment

Comparison of recovery rates of hatchery-spawned and wild-spawned yearling striped bass yielded inconsistent results. Fish were stocked in both the Sacramento River and San Pablo Bay. In both locations, for the 1984 year class, wild-spawned fish were recovered at a higher rate than hatchery-spawned fish (Figure 11). For the 1985 year class, hatchery-spawned fish were recovered at a higher rate than wild-spawned fish. Except for the 1984 year class stocked in San Pablo Bay, differences were statistically significant (χ^2 tests, *P* < 0.01). Overall (both areas and years combined) recovery rate of hatchery-spawned yearlings (0.00434) was significantly greater than for wild-spawned yearlings (0.00319) (χ^2 = 33.4, *P* < 0.001).

Cost of a Hatchery-Reared Fish in the Population and in the Creel

Cost of an age 3 hatchery-reared striped bass in the population, based on mean

survival rates to age 3 for fingerlings (0.009), advanced fingerlings (0.022), and yearlings (0.098) was $80.00, $64.09, and $15.82, respectively. Over the fishable lifetime of a year class, the cost of a hatchery-reared fish in the creel was $284.24 for fingerlings, $227.72 for advanced fingerlings, and $56.20 for yearlings.

DISCUSSION

As with any mark-recapture study, several assumptions must be met for results to be valid. Two of particular concern here are:

1. *Marked hatchery fish, unmarked hatchery fish, and wild fish are equally vulnerable to the fishery.* This assumption is probably true for fish of the same size (marked and unmarked hatchery fish). However, at the time of release, hatchery-reared yearlings tend to be larger than wild fish of the same year class and likely remain larger than wild fish of the same age; thus, they may be recruited to the fishery earlier. By omitting age 2 fish from the analysis, most problems with early recruitment of hatchery-reared yearlings were avoided. Although not all wild fish are legal sized at age 3, the lack of a consistent decrease in estimated hatchery contribution between ages 3 and 4 (one-sided sign test, P = 0.09) indicates that hatchery-reared striped bass were not over-represented in the catch at age 3 due to earlier recruitment.

2. *Marked fish retain their marks.* Double-marking experiments demonstrate that this assumption was violated. However, the same double-marking experiments provided results that allowed recoveries to be corrected for mark loss and nondetection.

Stocking large numbers of hatchery-reared fish has not halted the decline in abundance of striped bass that began in the mid-1970s. Since the beginning of striped bass stocking in 1981, abundance of legal-sized fish decreased from about 1 million to a low of 659,000 in 1993, only 488,000 of which were "naturally produced" (as opposed to stocked) fish. This decline is largely due to poor production of young fish probably due to reduced food production in the nursery area, entrainment losses into water diversions, and perhaps toxicity (Stevens et al. 1985). This has resulted in a downward spiral in which fewer adults produce fewer eggs, resulting in even less production of new fish. The decline has been exacerbated by decreasing survival of adults due to unknown causes.

The extent to which hatchery fish have replaced wild fish in the population, rather than supplemented them, is unknown. No reliable measures of wild striped bass survival from ages 1 to 3 are available, either before or after the initiation of stocking hatchery fish. Therefore, we have no estimate of changes in survival rate of wild fish associated with large-scale stocking.

Survival of hatchery-reared yearlings decreased as more fish were stocked; at the same time, mean size of hatchery-reared fish also decreased. Thus, we cannot differentiate between two competing hypotheses explaining the cause of the reduction in survival: (1) competition for limited resources, probably food or (2) poorer survival of small fish. Still, it is likely that hatchery-reared fish have made a positive contribution to the population and maintained adult abundance higher than it would have been without the stocking program.

The contribution of hatchery-reared striped bass to the legal-sized population in the

Sacramento-San Joaquin Estuary is greater than observed in other coastal systems where striped bass have been stocked. A hatchery evaluation study in the Chesapeake Bay system, using coded-wire tags, found that stocking phase-II juveniles from 1985 to 1990 from eight different hatcheries contributed 5–7% of the commercial catch in the state of Maryland in 1991–1993 (USDI and USDC 1995). Hatchery-reared fish contributed about 6% of the 1991 fall sport harvest in Maryland (USDI and USDC 1994). Near Montauk, New York, hatchery-reared striped bass from the Hudson River and Chesapeake Bay composed 3.5% of haul-seine catches in 1991 and 2.5% in 1992 (Waldman and Vecchio 1996). In contrast, hatchery-reared fish contributed up to 35% of a year class, and up to 26% of the total population of legal-sized fish, in the Sacramento-San Joaquin Estuary.

In our study, striped bass that were larger and older at stocking survived better than younger and smaller fish. This is similar to results from a study in Mississippi, in which striped bass > 45 g at stocking were recovered at a greater rate than smaller fish (Nicholson 1996). It is also consistent with results from the Savannah River, Georgia-South Carolina (Wallin and Van den Avyle 1995a). Although no yearlings were stocked there, fingerlings that were 180–225 mm TL at release survived 7–52 times better than 50–80 mm TL fingerlings. In turn, 50–80 mm TL fingerlings survived 10 times better than 15–25 mm TL fingerlings.

This same relationship has been found in other hatchery-produced fishes. Phase-II palmetto bass *M. saxatilis* x *M. chrysops* fingerlings exhibited post-stocking survival 23–200 times greater than phase-I fingerlings in the Escambia River, Florida (Yeager 1988). Survival of juvenile chinook salmon *Oncorhynchus tshawytscha* from three hatcheries on Sacramento River tributaries, as indexed by ocean catch and hatchery returns, increased as size at release increased (Reisenbichler et al. 1982). Also, yearling fall-run chinook salmon (mean weight = 58 g) contributed up to 12 times more to the fisheries than fingerling salmon (mean weight = 5 g) in studies of Feather River hatchery fish (Sholes and Hallock 1979).

Effects of stocking location were less clear cut and seemed to vary with size of fish at release. In 1 of the 3 years when the experiment was conducted, fingerlings released in the Sacramento River (freshwater) survived better that those released in San Pablo Bay (brackish water). There was no difference in survival between advanced fingerlings stocked in the Sacramento River and San Pablo Bay. More definitive results for fingerlings were obtained by Wallin and Van den Avyle (1995a) in the Savannah River, where long-term survival (≥ 1 year) of both advanced phase-I and phase-II fish was 3–11 times greater for fish stocked at freshwater sites than for those released in brackish water. Thus, young-of-the-year hatchery-reared striped bass survival may be increased if they are stocked in fresh water rather than at brackish-water sites.

For 7 years of stocking experiments combined, yearlings released in San Pablo Bay survived better than those released in the Sacramento River. In a 1-year experiment, yearlings released in the Sacramento River survived better than those stocked in the San Joaquin River (both freshwater sites). Finally, hatchery-spawned yearlings survived better when released in San Pablo Bay than when released in the Sacramento River, but there was no difference in survival of wild-spawned yearlings released in the same locations. For yearlings, our conclusion is that downstream stocking often results in higher survival than stocking in the fresh water of the delta. Higher salinity in San Pablo Bay at the time of stocking may ameliorate handling and transport stress, as observed in short-term (48 h) studies by Wallin and Van Den Avyle (1995b) in the Savannah River estuary, and lower turbidity there may increase predatory efficiency of yearling striped bass.

Results of comparisons of survival of hatchery-spawned and reared and wild-spawned, but hatchery-reared, yearlings were inconsistent. Data from only two year classes were available and these suggested higher survival for hatchery-spawned fish in one year and higher survival for wild-spawned fish in the other year. Intuitively, one might expect wild-spawned fish to survive better after stocking because of natural selection occurring during the time they reared in the wild before their capture at the Fish Facility screens. The subsequent period of hatchery rearing may have eliminated any fitness advantage they might have had relative to fish both spawned and reared in hatcheries.

As expected from differences in survival to recruitment, larger and older hatchery-reared striped bass were less expensive to put in the population and in the creel than smaller and younger fish. For stocking smaller fish to be economically efficient, the cost per yearling would have to be > 4.5 times the cost per advanced fingerling (ratio of mean estimated survival rates; Table 2) or > 11 times the cost per fingerling. In actuality, the cost ratios were 1.1 and 2.2, thus easily justifying the cost of rearing fish to the yearling stage. For comparison, Wallin and Van den Avyle (1995a) estimated that stocking larger fish would be economically justified only if the cost of phase-II fingerlings did not exceed about 7 times the cost of producing advanced phase-I fingerlings.

The estimated cost of $56 of putting a striped bass stocked as a yearling in the creel compares favorably with the estimated expenditure of $94 (Meyer Resources, Inc. 1985) by sport anglers to catch a striped bass. Thus, the benefit:cost ratio for stocking hatchery-reared yearlings is 1.68:1. This is probably an underestimate, as the cost of hatchery yearlings decreased to $1.17/fish in 1990 as more fish were produced (CDFG, unpublished

data), compared to the $1.55/fish in 1986–1987 used in our cost-comparison analysis. In contrast to our results, a study in the Patuxent River, Maryland that attempted to determine the relative costs and benefits of stocking phase-I and phase-II striped bass by sampling juveniles with beach seines up to about 12 weeks post-stocking was inconclusive; the range of phase-II fingerling survival was too broad to support generalizations (Dorazio et al. 1991).

These results provide a basis for defining an optimal striped bass stocking strategy for the Sacramento-San Joaquin Estuary and, by analogy, for other locations. The primary consideration is size and age of the stocked fish; stocking large yearlings is most successful and cost effective. Secondarily, some benefit may accrue from stocking in brackish-water areas, such as San Pablo Bay, especially if yearlings, rather than younger striped bass, are stocked. However, our results show no consistent survival advantage for wild-spawned, hatchery-reared fish compared to hatchery-spawned and reared fish.

Factors affecting survival of artificially reared striped bass continue to be studied through the coded-wire tagging of about 100,000 fish captured annually at the Fish Facility and reared in floating net pens. These fish are of wild origin, raised to yearling size in pens in the central estuary, and stocked in San Pablo Bay. Because they are raised in the more "natural" environment of brackish water, with at least limited access to natural prey items, some stress- and disease-related problems associated with intensive culture in freshwater may be reduced or eliminated. Future plans include rearing a combination of yearlings and 2-year-old striped bass in net pens and in hatcheries for release into the estuary. This will afford the opportunity to further evaluate the effect of size at stocking

and other factors on survival.

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REFERENCES

Albrecht, A. B. 1964. Some observations on factors associated with survival of striped bass eggs and larvae. California Fish and Game 50:100–113.

Anderson, J. C. 1966. Production of striped bass fingerlings. Progressive Fish Culturist 28:162–164.

Bonn, E. W., W. M. Bailey, J. D. Bayless, K. E. Erickson, and R. E. Stevens. 1976. Guidelines for striped bass culture. Southern Division, American Fisheries Society, Bethesda, Maryland.

Chadwick, H. K. 1963. An evaluation of five tag types used in a striped bass mortality rate and migration study. California Fish and Game 49:64–83.

Chadwick, H. K. 1967. Recent migrations of the Sacramento–San Joaquin River striped bass population. Transactions of the American Fisheries Society 96:327–342.

Chadwick, H. K. 1968. Mortality rates in the California striped bass population. California Fish and Game 54:228–246.

Cochran, M. D. 1992. Combined annual report, Central Valleys Striped Bass Hatchery, 1982–1985. California Department of Fish and Game, Inland Fisheries Administrative Report No. 92–4, Sacramento.

Collins, B. W. 1982. Growth of adult striped bass in the Sacramento-San Joaquin Estuary. California Fish and Game 68:146–159.

Dorazio, R. M., B. M. Florence, and C. M. Wooley. 1991. Stocking of hatchery-reared striped bass in the Patuxent River, Maryland: Survival, relative abundance, and cost-

effectiveness. North American Journal of Fisheries Management 11:435–442.

Farley, T. C. 1966. Striped bass, *Roccus saxatilis*, spawning in the Sacramento-San Joaquin River systems during 1963 and 1964. Pages 28–43 *in*: J. L. Turner, and D. W. Kelley, compilers. Ecological studies of the Sacramento-San Joaquin Delta, part II. California Department of Fish and Game, Fish Bulletin 136.

Lukens, R. R., L. C. Nicholson, and J. Y. Christmas, III. 1991. Success of juvenile striped bass in two bay systems in Mississippi: 1980–1984. Gulf Research Reports 8:317–327.

Meyer Resources, Inc. 1985. The economic value of striped bass, *Morone saxatilis*, chinook salmon, *Oncorhynchus tshawytscha*, and steelhead trout, *Salmo gairdneri*, of the Sacramento and San Joaquin River systems. California Department of Fish and Game, Anadromous Fisheries Branch Administrative Report 85-3, Sacramento.

Miller, L. W. 1974. Mortality rates for California striped bass (*Morone saxatilis*) from 1965–1971. California Fish and Game 60:157–171.

Minkkinen, S. P., C. P. Stence, and B. M. Richardson. 1995. The use of hatchery-produced striped bass for stock restoration and validation of stock parameters. Pages 555–556 *in:* H. L. Schramm, Jr., and R. G. Piper, editors. Uses and effects of cultured fishes in aquatic ecosystems. American Fisheries Society, Symposium 15, Bethesda, Maryland.

Nicholson, L. C. 1996. Striped bass restoration program for the tributaries of Mississippi's Gulf Coast. Sport Fish Restoration Act Annual Performance Report, Project No.F-95, 1 February 1995 through 31 January 1996. Gulf Coast Research Laboratory, Ocean Springs, Mississippi.

Orsi, J. J. 1971. The 1965–1967 migrations of the Sacramento-San Joaquin Estuary striped bass population. California Fish and Game 57:257–267.

Reisenbichler, R. R., J. D. McIntyre, and R. J. Hallock. 1982. Relation between size of chinook salmon, *Oncorhynchus tshawytscha*, released at hatcheries and returns to hatcheries and ocean fisheries. California Fish and Game 68:57–59.

Scofield, E. C. 1931. The striped bass of California (*Roccus lineatus*). California Department of Fish and Game, Fish Bulletin 29.

Sholes, W. H., and R. J. Hallock. 1979. An evaluation of rearing fall-run chinook salmon, *Oncorhynchus tshawytscha*, to yearlings at Feather River Hatchery, with a comparison of returns from hatchery and downstream releases. California Fish and Game 65:239–255.

Skinner, J. E. 1962. An historical review of the fish and wildlife resources of the San Francisco Bay area. California Department of Fish and Game, Water Projects Branch Report 1, Sacramento.

Stevens, D. E. 1966. Food habits of striped bass, *Roccus saxatilis*, in the Sacramento-San Joaquin Delta. Pages 68–96 *in*: J. L. Turner, and D. W. Kelley, compilers. Ecological studies of the Sacramento-San Joaquin Delta, part II. California Department of Fish and Game, Fish Bulletin 136.

Stevens, D. E. 1977. Striped bass (*Morone saxatilis*) monitoring techniques in the Sacramento-San Joaquin Estuary. Pages 91–109 *in:* W. Van Winkle, editor. Proceedings of the conference on assessing the effects of power-plant-induced

mortality on fish populations. Pergamon Press, New York.

Stevens, D. E., D. W. Kohlhorst, L. W. Miller, and D. W. Kelley. 1985. The decline of striped bass in the Sacramento-San Joaquin Estuary, California. Transactions of the American Fisheries Society 114:12–30.

Stevens, R. E. 1966. Hormone-induced spawning of striped bass for reservoir stocking. Progressive Fish Culturist 28:19–28.

Stevens, R. E. 1979. Striped bass culture in the United States. The Commercial Fish Farmer and Aquaculture News 5:10–14.

Thomas, J. L. 1967. The diet of juvenile and adult striped bass, *Roccus saxatilis*, in the Sacramento-San Joaquin River system. California Fish and Game 53:49–62.

Turner, J. L. 1976. Striped bass spawning in the Sacramento and San Joaquin rivers in central California from 1963 to 1972. California Fish and Game 62:106–118.

Turner, J. L., and H. K. Chadwick. 1972. Distribution and abundance of young-of-the-year striped bass (*Morone saxatilis*) in relation to river flow in the Sacramento-San Joaquin Estuary. Transactions of the American Fisheries Society 101:442–452.

USDI, and USDC (U.S. Department of the Interior, and U.S. Department of Commerce). 1994. Emergency Striped Bass Research Study, Report for 1992. Washington, D.C.

USDI, and USDC (U.S. Department of the Interior, and U.S. Department of Commerce). 1995. Emergency Striped Bass Research Study, Report for 1993. Washington, D.C.

Van Den Avyle, M. J., J. E. Wallin, and C. Hall. 1995. Restoration of the Savannah River striped bass population. Page 572 *in:* H. L. Schramm, Jr., and R. G. Piper, editors. Uses and effects of cultured fishes in aquatic ecosystems. American Fisheries Society,

Symposium 15, Bethesda, Maryland.

Waldman, J. R., and V. J. Vecchio. 1996. Selected biocharacteristics of hatchery-reared striped bass captured in New York ocean waters. North American Journal of Fisheries Management 16:14–23.

Wallin, J. E., and M. J. Van Den Avyle. 1995a. Long-term survival of three size-classes of striped bass stocked in the Savannah River, Georgia-South Carolina. Page 560 *in:* H. L. Schramm, Jr., and R. G. Piper, editors. Uses and effects of cultured fishes in aquatic ecosystems. American Fisheries Society, Symposium 15, Bethesda, Maryland.

Wallin, J. E., and M. J. Van Den Avyle. 1995b Interactive effects of stocking site salinity and handling stress on survival of striped bass fingerlings. Transactions of the American Fisheries Society 124:736–745.

Wooley, C. M., N. C. Parker, B. M. Florence, and R. M. Miller. 1990. Striped bass restoration along the Atlantic Coast: A multistate and federal cooperative hatchery and tagging program. Pages 775–781 *in:* N. C. Parker, and five others, editors. Fish marking techniques. American Fisheries Society, Symposium 7, Bethesda, Maryland.

Yeager, D. M. 1988. Evaluation of phase I and phase II hybrid striped bass in the Escambia River, Florida. Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies 41(1987):41–47.

Table 1. Summary of hatchery-reared striped bass stocked in the Sacramento-San Joaquin Estuary, California from 1981 to 1994.

	Number tagged or marked				Total stocked			
Year class	Fingerlings	Advanced fingerlings	Yearlings	Total	Fingerlings	Advanced fingerlings	Yearlings	Total
1980				0			62,640	62,640
1981			65,674	65,674			90,548	90,548
1982			91,216	91,216			101,351	101,351
1983			107,224	107,224			165,005	165,005
1984			288,564	288,564			417,495	417,495
1985		84,535	470,193	554,728		95,534	714,347	809,881
1986	370,612	93,163	215,814	679,589	521,264	109,125	490,605	1,120,994
1987	369,340	96,100	464,530	929,970	381,050	99,643	667,203	1,147,896
1988	439,196		353,897	793,093	465,910		864,725	1,330,635
1989	510,616		441,290	951,906	558,632		1,830,249	2,388,881
1990	450,086		363,912	813,998	474,743		2,879,122	3,353,865
Total	2,139,850	273,798	2,959,748	5,373,396	2,401,599	304,302	8,447,712	11,153,613

Table 2. Estimated survival of hatchery-reared striped bass from time of stocking in the Sacramento-San Joaquin Estuary to recruitment to the fishery at age 3.

	Size/age class		
Year class	**Fingerling**	**Advanced fingerling**	**Yearling**
1981			0.099
1982			0.175
1983			0.167
1984			0.065
1985		0.014	0.111
1986	0.008	0.034	0.088
1987	0.009	0.019	0.053
1988	0.012		0.097
1989	0.013		0.086
1990	0.004		0.041
Mean	0.009	0.022	0.098
Standard deviation	0.003	0.010	0.044

FIGURE CAPTIONS

Figure 1. Estimated abundance of legal-sized striped bass in the Sacramento-San Joaquin Estuary, 1969–1994.

Figure 2. Contribution of hatchery-reared fish to the 1981–1990 year classes of striped bass

in the Sacramento-San Joaquin Estuary.

Figure 3. Relation between fraction of hatchery-reared yearling striped bass in a year class and number of hatchery-reared yearlings stocked in the Sacramento-San Joaquin Estuary. Numbers beside data points are year classes.

Figure 4. Relation between estimated survival to age 3 of yearling hatchery-reared striped bass and number of hatchery-reared yearlings stocked in the Sacramento-San Joaquin Estuary. Numbers beside data points are year classes.

Figure 5. Comparison of recovery rates of fingerling and yearling hatchery-reared striped bass stocked in (a) the Sacramento River and (b) San Pablo Bay.

Figure 6. Comparison of recovery rates of advanced-fingerling and yearling hatchery-reared striped bass stocked in (a) the Sacramento River and (b) San Pablo Bay.

Figure 7. Comparison of recovery rates of fingerling and advanced-fingerling striped bass stocked in the Sacramento River.

Figure 8. Comparison of the effect of size at stocking on recovery rates of hatchery-reared yearling striped bass in the Sacramento-San Joaquin Estuary.

Figure 9. Comparison of recovery rates of (a) fingerling, (b) advanced-fingerling, and (c) yearling striped bass stocked in the Sacramento River and San Pablo Bay.

Figure 10. Comparison of recovery rates of (a) hatchery-spawned and (b) wild-spawned (collected at the John E. Skinner Fish Facility) striped bass stocked as yearlings in the Sacramento River and San Pablo Bay. Wild-spawned fish were reared in hatcheries.

Figure 11. Comparison of recovery rates of hatchery-spawned and wild-spawned (collected at the John E. Skinner Fish Facility) striped bass stocked as yearlings in (a) the Sacramento River and (b) San Pablo Bay. Wild-spawned fish were reared in hatcheries.