Abstract.—Declines in world fishery landings have prompted new interest in the use of cultured fishes to help replenish depleted fish populations. The hypothesis that hatchery releases can increase population size has at least two corollaries that need to be tested: 1) released cultured fish survive, grow, and contribute to recruitment; and 2) cultured fish do not displace wild stocks. The former corollary is considered here for striped mullet, *Mugil cephalus* L., in nursery habitats.

Results from pilot experiments were used to modify release strategies to test marine stock enhancement potential in Kaneohe Bay, Hawaii. Of 80,507 native, cultured, striped mullet fingerlings tagged with coded wire and released during spring and summer, 2,642 fish were recovered by cast-net sampling during 11 months. Recapture rate increased 600% compared with initial studies in Kaneohe Bay. This increase was the result of confining releases to the vicinity of fresh-water streams and of imposing a minimum size of 70 mm TL during summer releases. After 11 months, cultured fish represented 50% of the striped mullet in collections at the release site, 20% in a nursery habitat 1 km to the north, and 10% in a nursery 3 km north. The location of releases (stream mouth vs. upstream lagoon) significantly affected dispersal patterns but did not affect growth or recapture rate. This study corroborated earlier results which showed that the smallest fish released (45–60 mm) could survive relatively well if released in spring. At least three measures were needed to describe hatchery effect: 1) hatchery contribution (% cultured fish in samples), 2) catch per unit of effort for cultured and wild striped mullet, and 3) recovery rate (no. captured/no. released). This study documents that survival of cultured fish in coastal nurseries can be significantly improved by using information from pilot release experiments to revise release parameters.

Manuscript accepted 9 January 1996.
Fishery Bulletin 94:452–471 (1996).

Marine stock-enhancement potential in nursery habitats of striped mullet, *Mugil cephalus*, in Hawaii

Kenneth M. Leber
Steve M. Arce
David A. Sterritt*
Nathan P. Brennan**
The Oceanic Institute
Makapuu Point
Waimanalo, Hawaii 96795

The need for improved understanding and management of coastal fisheries is clear (New, 1991; NMFS, 1991, 1992; Anthony, 1993; Sissenwine and Rosenberg, 1993; Schnute and Richards, 1994). In 1990, growth in annual world fishery production peaked at 100 million metric tons (t) (FAO, 1992). Without more effective control of marine fisheries, seafood availability and recreational fishing opportunities are likely to decline at a rapid pace as demand increasingly outweighs supply during the next century (New, 1991; FAO, 1992). Ricker (1969) estimated maximum sustainable annual production levels of wild fisheries may be limited to 160 million t. More recently, the Food and Agriculture Organization of the United Nations (FAO) revised the estimate to 100 million t (WRI, 1990). Larkin (1993) suggests that sea farming could increase annual yields several fold over this level.

One form of sea farming, supplementing wild stocks with releases of cultured organisms (hatchery-based stock enhancement), may have considerable potential in marine and estuarine environments. Whether stock enhancement can help significantly increase world production levels of seafood is unclear (Schnute and Richards, 1994; Smedstad et al., 1994). Increased emphasis on quantitative evaluation is needed to determine the actual potential of stock enhancement. Norway and the United States first conducted large-scale hatchery releases of yolk-sac larvae of marine fishes at the end of the last century (Solemdal et al., 1984; Grimes, 1995); Japan followed with releases of hatched larvae of cod, herring, and king crab in the early 1900's (called "sea farming" in Japan; Kitada et al., 1992; Honma, 1993). A century later, the central issue remains largely unresolved—can propagation and release of cultured marine organisms into the wild increase coastal fish populations?

Although marine stocking programs in the USA were abandoned earlier this century for lack of a clear impact on fisheries landings, the potential for using hatchery releases to increase populations of coastal fishes was never critically tested (Richards and Edwards, 1986). Now, modern marking methods and new aquaculture capabili-

* Present address: Point Whitney Shellfish Laboratory, Washington Department of Fish and Wildlife, 1000 Point Whitney Road, Brinnon, WA 98320.

** Present address: Tennessee Technological University, Tennessee Cooperative Fishery-Research Unit, P.O. Box 5114, Cookeville, TN 38505.

ties provide the technologies required to quantify and evaluate marine stock enhancement (Jefferts et al., 1963; Buckley and Blankenship, 1990; and see Honma, 1993, for examples of growth in marine aquaculture). There is an emerging optimism that carefully implemented marine stock enhancement might be a useful fisheries management tool (e.g. Grimes, 1995). Use of cultured marine organisms to help replenish depleted coastal stocks has finally begun to receive empirical evaluation (Tsukamoto et al. 1989; Svåsand and Kristiansen, 1990; Svåsand et al., 1990, 1991; Bannister and Howard, 1991; Barlow and Gregg, 1991; Kitada et al., 1992, 1994; Iglesias and Rodríguez-Ojea, 1994; Jørstad et al., 1994, a and b; Nordeide et al., 1994; Smedstad et al., 1994; Stoner, 1994; Støttrup et al., 1994; Kent et al., 1995; Leber, 1995; Leber et al., 1995; Willis et al., 1995).

The hypothesis that hatchery releases can help increase marine fish populations has at least two corollaries that need to be tested. One is that cultured fishes released into coastal waters actually survive, grow, and contribute to recruitment. The other corollary is that cultured fish do indeed increase abundance rather than displace wild stocks. These two postulates are basic assumptions of stock-enhancement theory, yet both remain largely untested in coastal ecosystems (i.e. with organisms that reproduce in marine environments). The former corollary is the focus of this study, the latter is considered elsewhere (Leber et al., 1995).

A series of workshops was held to select species for immediate stock-enhancement research in Hawaii. The species given priority was Pacific threadfin, *Polydactylus sexfilis*, an inshore carnivore. An inshore herbivore, striped mullet, *Mugil cephalus*, ranked second in this semi-quantitative selection process (Leber[1]). We chose to begin field experiments with striped mullet because it ranked high in the selection process and culture techniques were available. We expected to apply lessons learned about stock enhancement to Pacific threadfin once culture techniques became available.

To design a rigorous test, data would be needed from pilot releases to define effective release strategies. Fish size-at-release (SAR) and the timing of releases were important choices that needed to be made, as Hager and Noble (1976) and Bilton et al. (1982) had already shown with coho salmon released into streams in the Pacific northwest. Releasing fish into coastal environments would also require careful consideration of release habitat. If any of these three variables affected survival of released fish, they would also affect the power of any test of stock-enhancement potential. In Hawaii, a series of pilot release experiments were conducted to identify effects of release magnitude, SAR, release habitat, and release season on survival and contribution of cultured striped mullet to wild stock abundance (Leber, 1995; Oceanic Institute[2]; Leber et al.[3]). The results of those pilot releases were used to design the present study, which is to test the first corollary—that cultured fish make a substantial contribution to a marine fish population in Hawaii.

As pilot release-recapture experiments began in Hawaii, Tsukamoto et al. (1989) published results that indicated that SAR affected survival of red sea bream, *Pagrus major*, juveniles released into News Bay, Japan. In 1990, Svåsand and Kristiansen (1990) showed similar results with cod, *Gadus morhua*, released into Norwegian fjords. In 1990, a similar pattern was observed in Hawaii following summer releases of about 40,000 tagged striped mullet into each of two embayments on Oahu, Maunalua Bay and Kaneohe Bay (Leber, 1995). Work with striped mullet revealed that recapture rates approached zero when cultured fish smaller than 60-mm total length (TL) were released in summer or fall months. These results ruled out the alternative of stocking newly hatched fry or postlarvae in an experimental test of the stock-enhancement concept in Hawaii. Pilot releases in Hawaii also revealed that survival of cultured mullet was strongly affected by release habitat and release season (Leber, 1995; Leber and Arce, in press; Leber et al.[3]). Hatchery release studies with marine fishes in Norway, Florida, and California (Svåsand and Kristiansen, 1990; Drawbridge et al., 1995; Willis et al., 1995) and with cultured conch released in the Caribbean (Stoner, 1994) have shown substantial effects of release strategies on survival in coastal environments.

Based on the results of pilot hatchery releases in Kaneohe Bay, an experiment was designed to incorporate improved release strategies and to evaluate the potential of using hatchery releases to increase significantly juvenile striped mullet recruitment in Kaneohe Bay, the largest estuary in Hawaii. Criteria for success were the following: 1) cultured fish released in this study represented a substantial pro-

[1] Leber, K. M. 1994. Prioritizing marine fishes for stock enhancement in Hawaii. The Oceanic Institute, Honolulu, HI, 46 p.

[2] Oceanic Institute. 1990. Stock enhancement of marine fish in the State of Hawaii (SEMFISH, Phase II). Annual report to NMFS, February 1989–June 1990, Waimanalo, Hawaii, 106 p.

[3] Leber, K. M., S. M. Arce, H. L. Blankenship, and N. P. Brennan. 1996. Influence of release season on size-dependent survival of cultured striped mullet, *Mugil cephalus*, in a Hawaiian estuary. In review.

portion (at least 20%) of the juvenile striped mullet in net samples 4 months after release; 2) there was a persistence of cultured fish in net samples throughout the study; and 3) growth was comparable to measured rates in wild juveniles. If these criteria were met, it would be reasonable to assume that cultured fish had substantially affected juvenile recruitment at the study site.

This study was conducted in and around fresh water tributaries, the preferred nursery habitat for striped mullet. Striped mullet are catadromous and begin to move out of their nursery habitats as they approach maturity (Blaber, 1987). In Hawaii, yearling juveniles begin to move out of the intertidal zone and out of shallow shore zones of streams by about February or March (Major, 1978; Leber, 1995; Oceanic Institute[4]). Striped mullet reach advanced sexual development in fresh water but must migrate to the sea to spawn (Blaber, 1987). Annual recruitment into inshore nursery habitats of young-of-the-year wild mullet occurs in spring in Hawaii (Major, 1978).

Methods

Hatchery releases

Striped mullet were spawned from wild broodstock at The Oceanic Institute and reared to fingerling size for spring and summer releases. Batches of striped mullet eggs were hatched about every six weeks over a five-month period. Larval striped mullet from each batch were hatched and cultured in 5,000-L cylindrical tanks with conical bottoms for 45 days. Stage-1 juveniles (45 days old, 20 mm TL) were transferred to 8,000-L circular tanks and nursed for 40 days to stage-2 juveniles (85 days old, 40 mm TL). Stage-2 juveniles were transferred to 30,000-L circular tanks and nursed to tagging size (45–130 mm TL). In culture tanks, growth rates averaged 0.5 mm TL/day.

A release-recapture experiment was performed to evaluate recapture rates of cultured striped mullet. Release magnitude, release location, release season, and size of fish released were determined from results of 1990 and 1991 pilot studies in Kaneohe Bay (Leber, 1995; Leber et al.[3]). During 4 May through 29 May 1992, and again from 13 July through 7 August 1992, juveniles were harvested from culture tanks, graded into five different length groups (ranging from 45 mm to 130 mm TL) by using commercial bar graders and tagged with binary coded-wire tags (CWT) (Northwest Marine Technology, Inc., Olympia, WA). Prior to tagging, fish were provided a 2-day period to recover from stress of harvesting and size grading. About 80,500 tagged fish were released into Kaneohe Bay.

Tags identified year and season of release, SAR, release habitat, release lot (date), and number of fish released per treatment condition. Fish were tagged in batches, with a different code for each season-SAR-site-lot combination. Tags were implanted in the snout area with an automatic injector with head molds designed specifically for striped mullet.

For each release season and SAR combination, the experiment was replicated with three release lots at each of two release locations in Kahaluu Stream (Fig. 1), where the greatest recruitment of wild mullet in Kaneohe Bay had been reported (Leber, 1995; Oceanic Institute[4]). In May, fish of all five size intervals were released in each lot (45–60 mm; 60–70 mm; 70–85 mm; 85–110 mm; and 110–130 mm). Only fish of

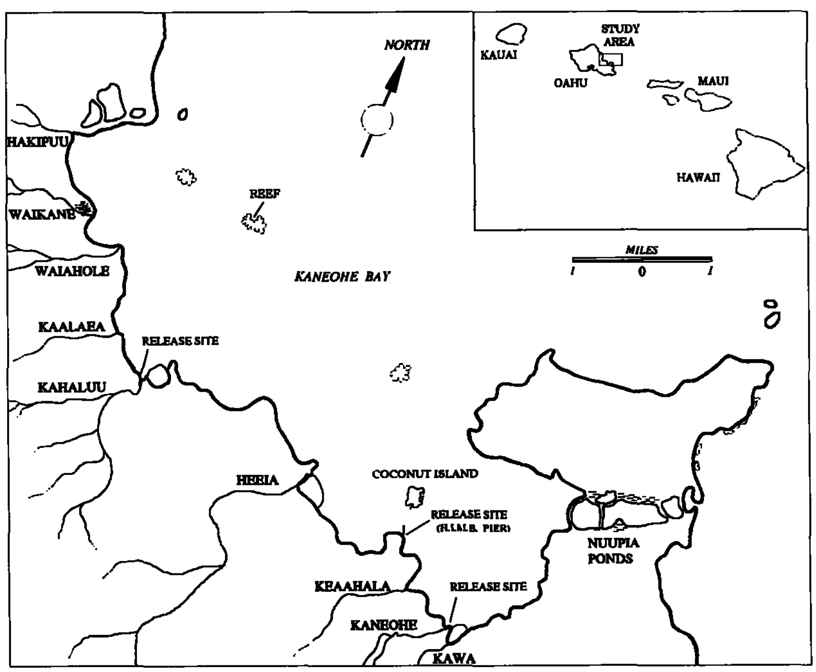

Figure 1

Map of Kaneohe Bay showing pilot study release sites and nursery habitats where monthly cast-net collections were conducted. In this study, all releases were made at Kahaluu Stream, a principal nursery habitat for striped mullet in Kaneohe Bay.

[4] Oceanic Institute. 1991. Stock enhancement of marine fish in the State of Hawaii (SEMFISH Phase III). Annual report to NMFS, June 1990–June 1991. Waimanalo, Hawaii, 107 p.

the three largest size intervals were released in summer (none <70 mm TL). There was size variation in all batches of mullet reared for this study. However, the primary difference among the five size intervals of fish released was fish age.

Replicate release lots were introduced biweekly for a 3- to 4-week period in both spring and summer. Fish were transported and then released simultaneously at the stream inlet and 300 m upstream in a 10-ha lagoon. Numbers of tagged and released fish varied between seasons and among size intervals released but were held nearly constant among release lots and between release sites (Table 1). Between 10,200 and 15,100 tagged fish were released in each of six release lots. Releases were conducted around mid-day or early afternoon. Bottom salinities at release sites ranged from 12 to 25 ppt. All releases were made near the shoreline in water from 0.5 to 1.5 m deep.

Previous studies revealed a CWT retention rate of 97% for striped mullet during 12 months following tagging (Oceanic Institute[4]). To verify tag-retention rates in this study, at least 5% of fish tagged for each release lot were randomly subsampled prior to each release. These subsamples, totalling 4,264 tagged fish, were retained in 12 tanks for up to 4 months; fish were checked monthly to verify when % tag retention stabilized (Blankenship, 1990).

Tagged fish from the 1991 study were also recovered in this study. Methods in that study were essentially identical to those here, with two exceptions: 1) in 1991, fish of all five size intervals were released in both spring and summer; 2) 1991 release sites included Kahaluu Stream mouth and Kaneohe Stream mouth (Leber et al.[3]). The mouth of Kaneohe Stream lies 11.6 km south of Kahaluu Stream mouth.

Monitoring

To evaluate the effect of releases on juvenile abundance, collections were made monthly with cast nets in four Kaneohe Bay nursery habitats, except for July (when summer releases were conducted). We began to monitor abundances of released and wild striped mullet in Kaneohe Bay on 8 June 1992 and continued to do so for 10 months. Each field collection was conducted during a 1-wk period. Collections were made during the day during an 8-h period at each nursery site (sampling station). Stations were established in the vicinity of documented striped mullet nursery habitats at various tributaries throughout the bay (Oceanic Institute[4]).

To standardize collection effort, two substations were established at each station—one 200 to 300 m upstream, the other in the bay seaward of the stream mouth and on subtidal reef flats running along the bay shore on both sides of the stream mouth. Within substations, 15 cast-net throws were made. A total of 120 cast-net samples were taken each month. To broaden the range of microhabitats and fish size-

Table 1

Summary statistics for 80,507 fish tagged and released in 1992 to evaluate hatchery releases in Kaneohe Bay. Unique batch codes were used to identify fish from each cell in the matrix. Spring release lot 1 occurred on 4 May, lot 2 on 15 May, and lot 3 on 29 May. Summer release lot 1 occurred on 13 July, lot 2 on 24 July, and lot 3 on 7 August.

		Release season								
		Spring release lot				Summer release lot				
Release site	Size at release	1	2	3	Total	1	2	3	Total	Grand total
Kahaluu (upstream at lagoon)	45–60 mm	2,356	2,368	2,277	7,001	0	0	0	0	7,001
	60–70 mm	2,372	2,375	2,371	7,118	0	0	0	0	7,118
	70–85 mm	1,595	1,594	1,591	4,780	2,867	2,497	4,063	9,427	14,207
	85–110 mm	807	807	805	2,419	2,863	2,493	2,540	7,896	10,315
	110–130 mm	398	399	399	1,196	250	125	72	447	1,643
	Subtotal	7,528	7,543	7,443	22,514	5,980	5,115	6,675	17,770	40,284
Kahaluu Stream (mouth)	45–60 mm	2,356	2,369	2,321	7,046	0	0	0	0	7,046
	60–70 mm	2,361	2,370	2,344	7,075	0	0	0	0	7,075
	70–85 mm	1,596	1,593	1,599	4,788	2,878	2,494	4,069	9,441	14,229
	85–110 mm	806	806	805	2,417	2,848	2,500	2,540	7,888	10,305
	110–130 mm	396	399	399	1,194	249	125	0	374	1,568
	Subtotal	7,515	7,537	7,468	22,520	5,975	5,119	6,609	17,703	40,223
Grand total		15,043	15,080	14,911	45,034	11,955	10,234	13,284	35,473	80,507

ranges sampled, two different-size cast nets were used. Of the 15 casts per substation, 10 were made with a 5-m diameter, 10-mm mesh net, and five casts were made with a 3-m diameter, 6-mm mesh net. The smaller net was more effective in narrow upstream habitats.

We used stratified-random sampling; cast nets were thrown over schools of mullet juveniles, rather than thrown randomly. Random sampling yielded few wild mullet and very few tagged individuals. Cultured and wild striped mullet schooled together in fairly low densities within these clear-water nursery habitats, and our collections targeted these schools. Nevertheless, data used to determine recapture rates and proportions of tagged mullet in samples were randomly distributed because there was no a-priori indication that schools, once sighted, contained tagged individuals.

Mullet sampled in these collections were measured and checked for tags with a portable tag detector (Northwest Marine Technology, Inc.). All tagged mullet were placed on ice and returned to the laboratory for size measurement and tag analysis. Wild fish were counted, measured, and released at the sample site. After extraction, the binary codes were read by a technician with a binocular microscope (40×). All tag codes were verified with a second (blind) reading by a another technician.

Data were analyzed with SYSTAT software (Wilkinson, 1990). A randomized-block design ANOVA was used to compare means. Treatments (SAR, release microhabitat) were blocked over time (3 release lots) within season (spring and summer). Proportions were arcsine transformed. Orthogonal contrasts were used to compare means (Sokal and Rohlf, 1981). SYSTAT Basic was used to write tag decoding algorithms. For each recaptured fish, the algorithms identified SAR, release microhabitat, release date, release lot, and number of fish released per treatment-lot combination on the basis of the binary tag codes. An error-check algorithm was also written. Variance estimates are expressed throughout as standard errors.

Results

Recapture summary

A total of 2,985 tagged cultured mullet were recaptured during the 11-month period of this study (Table 2). Of these, 2,642 were cultured fish from the present study (1992 releases). None of the fish released in 1992 were recaptured at Kaneohe Stream. From the tag codes it was determined that 304 (10.2%) of the 2,985 tagged fish collected had been released in

Table 2

Numbers of tagged cultured striped mullet recovered in cast-net samples made in Kaneohe Bay. 304 of the 2,985 cultured fish recaptured were released in 1991, the remainder in 1992. None of the fish released in 1992 were captured at Kaneohe Stream. Sites are arranged from north (Waiahole Stream) to south (Kaneohe Stream). 30 cast-net throws were made at each station monthly.

Collection site	Source	Jun	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Total	Mean	SE
Waiahole Stream	Wild	126	169	141	121	10	65	54	13	47	26	772	77.2	18.2
	Cultured	29	26	27	64	15	47	32	8	7	3	258	25.8	6.0
	%Cultured	18.7	13.3	16.1	34.6	60.0	42.0	37.2	38.1	13.0	10.3	25.0	28.3	5.2
Kaalaea Stream	Wild	84	154	66	172	85	58	48	34	24	20	745	74.5	16.4
	Cultured	111	221	83	58	128	74	60	46	22	5	808	80.8	19.5
	%Cultured	56.9	58.9	55.7	25.2	60.0	56.1	55.6	57.5	47.8	20.0	52.0	49.4	4.6
Kahaluu Stream	Wild	258	99	82	69	65	49	34	64	32	28	780	78.0	24.7
(1991 and 1992	Cultured	231	376	237	188	164	111	136	132	37	28	1640	164.0	32.4
release site in	% Cultured	47.2	79.2	73.7	73.2	71.6	69.4	80.0	67.4	53.6	50.0	67.8	66.5	3.8
N. Kaneohe Bay)														
Kaneohe Stream	Wild	58	36	55	56	50	45	35	27	48	40	450	45.0	3.3
(1991 release site	Cultured	41	29	42	42	33	21	33	11	19	8	279	27.9	4.0
in S. Kaneohe Bay)	%Cultured	41.4	44.6	43.3	42.9	39.8	31.8	48.5	29.0	28.4	16.7	38.3	36.6	3.1
All streams	Wild	526	458	344	418	210	217	171	138	151	114	2747	274.7	47.2
	Cultured	412	652	389	352	340	253	261	197	85	44	2985	298.5	55.2
	%Cultured	43.9	58.7	53.1	45.7	61.8	53.8	60.4	58.8	36.0	27.8	52.1	50.0	3.5

Kaneohe Bay in 1991 as part of a previous pilot study (Leber et al.[3]). Tags from 39 (1.3%) of the recaptured fish were lost during the extraction process. These 39 cultured fish were released either in 1991 or 1992 but could not be further identified and were excluded from our analyses. Thus, the decoded tag data are based on 2,946 tags.

Tag retention in the subsampled fish held for 4 months averaged 97.9% (±0.6 SE, n=12 tanks). With one exception (92.6%, lot 1, lagoon release), all tag retention rates within release lots exceeded 97%. After capture data were adjusted for the 2.1% tag loss, a total of about 2,697 cultured fish from the 1992 releases were actually captured (3.3% of the 80,507 fish released in this study).

Tagged cultured fish represented about 50% of the 5,732 wild and cultured mullet collected from the four study sites (Table 2). Proportions of cultured mullet in Kahaluu samples remained >50% of the total (wild and cultured) mullet sampled in collections throughout the study and were ≥70% in six of ten collections (Table 2). Proportions of hatchery fish were also high at two streams north of the release site.

Recovery of yearlings released in 1991

Sampling periods in the present study ranged from 47 weeks to 100 weeks after the 1991 releases. Most (86%) fish from 1991 releases were collected at Kaneohe Stream, where they represented a high proportion of 1-yr-old mullet at that site throughout their second year in the wild (Table 3). Only 42 of the 304 fish from the 1991 release were collected outside Kaneohe Stream. These 42 fish accounted for <3% of the cultured fish collected at any other site. Thus, some fish from 1991 releases continued to occupy juvenile mullet nursery habitats well into their second year.

Marine enhancement impact: 1992 releases

Release impact in nursery habitats About 90% of the 2,946 tags recovered and decoded were from striped mullet released at Kahaluu in 1992. These fish made a substantial contribution to juvenile recruitment in three nursery habitats in the north end of the bay: Kahaluu Stream, Kaalaea Stream, and Waiahole Stream (Table 2).

Impact of the test release was greatest at the release site, Kahaluu Stream; there was a trend towards reduced impact with shoreline distance away from that site. Cultured fish consistently outnumbered wild fish at the release site and averaged 66% of the mullet in monthly collections at Kahaluu. After 11 months in the wild, cultured fish still represented 50% of the mullet sampled at Kahaluu. Greatest impact outside of the release site was seen at Kaalaea, 1 km north of Kahaluu Stream, where cultured fish averaged about 50% of the mullet sampled. A substantial effect was also apparent in Waiahole Stream, a mullet nursery habitat 3 km north of Kahaluu Stream, where cultured fish averaged 28% of the mullet sampled. Proportions of cultured mullet in collections were stable through time at all four nursery habitats sampled until spring, when annual recruitment of wild mullet began. Numbers of both wild and cultured fish from the 1992 year class declined in samples in spring at all nursery sites (Table 2).

Table 3

Movement patterns following 1991 releases of 91,245 tagged cultured mullet in Kaneohe Bay (half at Kahaluu Stream, half at Kaneohe Stream.) Release season and release site are identified for 304 tagged fish recovered at the various collection (recapture) sites throughout the Bay. Recapture sites (and distances travelled) are ordered geographically within collection dates, from the northernmost site (Waiahole Stream) to the southernmost site (Kaneohe Stream) at which tagged fish were collected (see Fig. 1). Data are totals (n) recaptured in 300 cast-net samples per site taken over the 10-mo. study period.

Collection date (weeks after release)	Recapture site	Kahaluu release		Kaneohe release		Collection date (weeks after release)	Recapture site	Kahaluu release		Kaneohe release	
		n	Distance (km)	n	Distance (km)			n	Distance (km)	n	Distance (km)
Spring release						**Summer release**					
Weeks 57–100	Waiahole	—	3.05	3	15.00	Weeks 47–91	Waiahole	1	3.05	3	15.00
	Kaalaea	3	0.98	—	12.59		Kaalaea	—	0.98	—	12.59
	Kahaluu	26	0	—	12.04		Kahaluu	6	0	—	12.04
	Kaneohe	—	11.58	111	0		Kaneohe	1	11.58	150	0
	Total	29		114			Total	8		153	

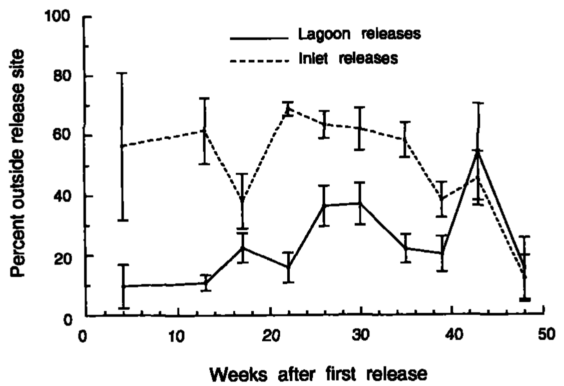

Figure 2

Release microhabitat effect on dispersal of released cultured fish. Proportions (± SEM, n=6 lots) of cultured striped mullet recaptured outside of the release habitat, Kahaluu Stream, following downstream (inlet) releases at the shore next to the stream mouth, and releases 300 m upstream (lagoon).

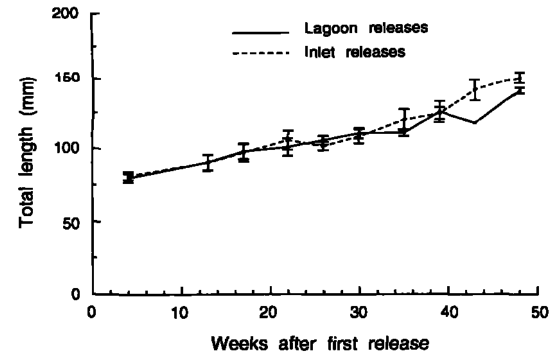

Figure 3

Mean length (TL [±SEM, n=6]) of cultured striped mullet recovered in net samples made over the course of the study, for individuals that were 70–85 mm TL when released.

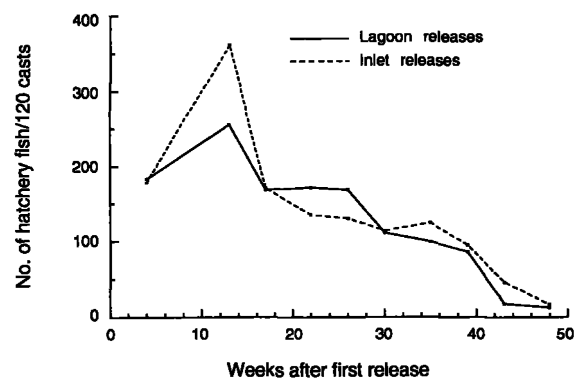

Figure 4

Catch per unit of effort (CPUE) for cultured striped mullet from collections made at four nursery habitats (combined data) in Kaneohe Bay, including the release site. Total number of tagged fish recaptured in 120 cast-net samples taken monthly (30 samples per month at each nursery habitat) compared with those taken over the 11-mo study period.

Release microhabitat effect on enhancement impact Initial habitat selection was strongly affected by release microhabitat. There was greater dispersal away from the release site by fish released next to the inlet of Kahaluu Stream than by fish released about 300 m upstream in the lagoon (Fig. 2.) This pattern was similar following both spring and summer releases (Table 4). Most fish released upstream remained in Kahaluu Stream throughout the study, whereas most fish from the inlet releases moved to other nursery sites in the bay. This difference in dispersal patterns was statistically significant by the second collection date (P<0.003, n=6 release lots per treatment [3 spring + 3 summer]) and was observed through mid February 1993 (P<0.01 in collections Aug, Oct, and Jan; P<0.05 in Nov, Dec, and Feb; not significant in Jun, Sep, Mar, and Apr).

Recapture rates and growth rates were unaffected by release microhabitat. Growth curves for fish released at the inlet and lagoon were intermingled (Fig. 3) as were plots of numerical abundances of cultured fish in collections (Fig. 4). Statistical comparisons were nonsignificant (n=6, P>0.08) for all collection dates.

SAR and release-season effects on enhancement impact

Overall SAR effect on recapture rates Fish size-at-release affected survival of mullet released in this study. The smallest size group (45–60 mm TL) had significantly reduced survival in comparison with other sizes (Fig. 5). Fish <60 mm TL were recaptured at less than half the frequency of larger fish released (Fig. 5; P<0.001; P<0.002 in orthogonal contrast in a comparison of SAR-1 with SAR1-2, -3, and -4 combined; n=6 with recapture data from spring and summer releases combined). For the four SAR groups >60 mm TL (in the aggregate data set, spring and summer releases combined), there were no significant differences among recapture frequencies (P>0.30 for any comparison, spring and summer releases combined).

Table 4

Movement patterns following 1992 releases at Kahaluu Stream in Kaneohe Bay. Release season and release sites (inlet release was at the mouth of Kahaluu Stream and lagoon release was about 300 meters upstream in a 10-hectare lagoon) are identified for tagged fish recovered at the various collection (recapture) sites throughout the Bay. Recapture sites (and distances travelled) are ordered geographically within collection dates, from the northernmost site (Waiahole Stream) to the southernmost site (Kaneohe Stream) at which tagged fish were collected (see Fig. 1). Monthly data are totals (*n*) per 30 samples per site, organized by the average time (weeks after release) that fish had been in the wild prior to collection.

Spring release

Collection date (weeks after release)	Recapture site	Inlet release *n*	Inlet release Distance (km)	Lagoon release *n*	Lagoon release Distance (km)
8–12 Jun 92	Waiahole	25	3.1	4	3.2
	Kaalaea	100	1.0	10	1.1
	Kahaluu	53	0	169	.1
3	Kaneohe	—	11.6	—	11.7
	Total	178		183	
17–21 Aug 92	Waiahole	18	3.1	—	3.2
	Kaalaea	131	1.0	10	1.1
	Kahaluu	25	0	67	.1
13	Kaneohe	—	11.6	—	11.7
	Total	174		77	
21–25 Sep 92	Waiahole	11	3.1	4	3.2
	Kaalaea	38	1.0	13	1.1
	Kahaluu	34	0	54	.1
18	Kaneohe	—	11.6	—	11.7
	Total	83		71	
19–23 Oct 92	Waiahole	14	3.1	3	3.2
	Kaalaea	28	1.0	5	1.1
	Kahaluu	20	0	81	.1
22	Kaneohe	—	11.6	—	11.7
	Total	62		89	
16–23 Nov 92	Waiahole	3	3.1	2	3.2
	Kaalaea	25	1.0	17	1.1
	Kahaluu	17	0	46	.1
26	Kaneohe	—	11.6	—	11.7
	Total	45		65	
14–18 Dec 92	Waiahole	5	3.1	5	3.2
	Kaalaea	17	1.0	8	1.1
	Kahaluu	19	0	37	.1
30	Kaneohe	—	11.6	—	11.7
	Total	41		50	
11–15 Jan 93	Waiahole	8	3.1	4	3.2
	Kaalaea	21	1.0	2	1.1
	Kahaluu	17	0	27	.1
34	Kaneohe	—	11.6	—	11.7
	Total	46		33	

Summer release

Collection date (weeks after release)	Recapture site	Inlet release *n*	Inlet release Distance (km)	Lagoon release *n*	Lagoon release Distance (km)
17–21 Aug 92	Waiahole	6	3.1	1	3.2
	Kaalaea	67	1.0	12	1.1
	Kahaluu	114	0	165	.1
3	Kaneohe	—	11.6	—	11.7
	Total	187		178	
21–25 Sep 92	Waiahole	10	3.1	2	3.2
	Kaalaea	12	1.0	15	1.1
	Kahaluu	65	0	80	.1
8	Kaneohe	—	11.6	—	11.7
	Total	87		97	
19–23 Oct 92	Waiahole	32	3.1	14	3.2
	Kaalaea	20	1.0	5	1.1
	Kahaluu	21	0	63	.1
13	Kaneohe	—	11.6	—	11.7
	Total	73		82	
16–23 Nov 92	Waiahole	3	3.1	6	3.2
	Kaalaea	49	1.0	35	1.1
	Kahaluu	33	0	62	.1
16	Kaneohe	—	11.6	—	11.7
	Total	85		103	
14–18 Dec 92	Waiahole	18	3.1	18	3.2
	Kaalaea	35	1.0	13	1.1
	Kahaluu	20	0	30	.1
20	Kaneohe	—	11.6	—	11.7
	Total	73		61	
11–15 Jan 93	Waiahole	14	3.1	5	3.2
	Kaalaea	27	1.0	10	1.1
	Kahaluu	37	.1	51	.1
24	Kaneohe	—	11.6	—	11.7
	Total	78		66	
15–19 Feb 93	Waiahole	3	3.1	4	3.2
	Kaalaea	23	1.0	6	1.1
	Kahaluu	33	0	23	.1
29	Kaneohe	—	11.6	—	11.7
	Total	59		33	
15–19 Mar 93	Waiahole	2	3.1	4	3.2
	Kaalaea	11	1.0	2	1.1
	Kahaluu	16	0	4	.1
34	Kaneohe	—	11.6	—	11.7
	Total	29		10	

Table 4 (continued)

Collection date (weeks after release)	Recapture site	Inlet release n	Inlet release Distance (km)	Lagoon release n	Lagoon release Distance (km)	Collection date (weeks after release)	Recapture site	Inlet release n	Inlet release Distance (km)	Lagoon release n	Lagoon release Distance (km)
Spring release						**Summer release**					
16–19 Dec 93	Waiahole	—	3.1	1	3.2	12–16 Apr 93	Waiahole	—	3.1	2	3.2
	Kaalaea	13	1.0	4	1.1		Kaalaea	—	1.0	2	1.1
	Kahaluu	23	0	48	.1		Kahaluu	8	0	5	.1
39	Kaneohe	—	11.6	—	11.7	38	Kaneohe	—	11.6	—	11.7
	Total	36		53			Total	8		9	
15–19 Mar 93	Waiahole	—	3.1	1	3.2						
	Kaalaea	8	1.0	1	1.1						
	Kahaluu	9	0	6	.1						
43	Kaneohe	—	11.6	—	11.7						
	Total	17		8							
12–16 Apr 93	Waiahole	—	3.1	—	3.2						
	Kaalaea	3	1.0	—	1.1						
	Kahaluu	6	0	4	.1						
47	Kaneohe	—	11.6	—	11.7						
	Total	9		4							
Grand totals through Week 39	Waiahole	84	3.1	23	3.2	Grand totals through Week 38	Waiahole	88	3.1	56	3.2
	Kaalaea	373	1.0	69	1.1		Kaalaea	244	1.0	100	1.1
	Kahaluu	208	0	529	.1		Kahaluu	347	0	483	.1
	Kaneohe	—	11.6	—	11.7		Kaneohe	—	11.6	—	11.7
	Total	665		621			Total	679		639	

Effect of release season Although recapture rates among SAR groups >60 mm appeared similar in the aggregate data set, an SAR effect was apparent when data were collapsed within release seasons (Table 5). To clarify survival and the interactive effect of release season with SAR, only fish that survived at least 16 weeks are included in Figures 6, 7, and 8. This provides a picture of those cultured fish that remain in the population from 4 months on, having survived initial causes of mortality in the wild, and that have the potential to affect adult abundances.

All sizes released in spring and summer were prominent in cast-net collections (Table 5). As expected following spring releases (Leber et al.[3]), no direct relationship was apparent between SAR and recapture rates. However, recapture rates (from week 16 on) were significantly less for the smallest size group released than for SAR groups 2, 3, and 5 (Fig. 6, $P<0.02$).

Summer releases resulted in better recovery of the largest size group released (Fig. 7, 110–130 mm TL; $P<0.04$; marginally significant). There was also a trend (nonsignificant) towards better recovery of the three largest SAR groups when released in summer rather than in spring (Fig. 8).

Growth of fish released in spring was comparable with that of fish released in summer (Fig. 9). Data in Figure 9 are for fish from the median SAR group (70–85 mm TL), for which the greatest amount of data was available. This growth comparison is representative of the other sizes released in both seasons.

Comparison with 1990 and 1991 release impact There was substantially greater impact on juvenile abundances in Kaneohe Bay following 1992 releases than after pilot releases in 1990 (Leber, 1995) and in 1991 (Leber et al.[3]). Proportions of cultured fish at Kahaluu 10 months after releases increased from about 3% following 1990 releases to 10% after 1991 releases, to about 50% in the present study (Fig. 10).

The general pattern following releases was similar in all years—an initial increase in proportions of cultured fish in samples, followed by a decline over the next year. However, there were two principal differences in 1992: 1) July releases in 1992 caused a considerably greater increase in abundance than in

Table 5

Numbers of tagged fish released in 1992 and recovered from each treatment group by size at release within release season at Kahaluu Stream in Kaneohe Bay. Data are totals (*n*) recaptured and recapture frequencies (% recap. [*n* recaptured/*n* released]), organized by the average time (weeks after release) that fish had been in the wild prior to collection. Note that summer releases followed spring releases by 10 weeks.

Collection date (weeks after release)	Size at release	Total recap. *n*	% recapt.	Collection date (weeks after release)	Size at release	Total recap. *n*	% recapt.	Grand total	Grand total % recap.
Spring release				**Summer release**					
8–12 Jun 92	45–60 mm	14	0.10	17–21 Aug 92	45–60 mm	—	—	14	0.10
	60–70 mm	98	0.69		60–70 mm	—	—	98	0.69
	70–85 mm	131	1.37		70–85 mm	161	0.85	292	1.03
3	85–110– mm	89	1.84	3	85–110 mm	192	1.22	281	1.36
	110–130 mm	29	1.21		110–130 mm	12	1.46	41	1.28
	Total	361	0.80		Total	365	1.03	726	0.90
				21–25 Sep 92	45–60 mm	—	—	—	—
					70–85 mm	—	—	—	—
					70–85 mm	76	0.40	76	0.40
				8	85–110 mm	106	0.68	106	0.68
					110–130 mm	2	0.24	2	0.24
					Total	184	0.52	184	0.52
17–21 Aug 92	45–60 mm	30	0.21	19–23 Oct 92	45–60 mm	—	—	30	0.21
	60–70 mm	98	0.69		60–70 mm	—	—	98	0.69
	70–85 mm	77	0.80		70–85 mm	82	0.43	159	0.56
13	85–110 mm	37	0.77	13	85–110 mm	70	0.51	107	0.52
	110–130 mm	9	0.38		110–130 mm	3	0.37	12	0.37
	Total	251	0.56		Total	155	0.44	406	0.50
21–25 Sep 92	45–60 mm	20	0.14	16–23 Nov 92	45–60 mm	—	—	20	0.14
	60–70 mm	55	0.39		60–70 mm	—	—	55	0.39
	70–85 mm	49	0.51		70–85 mm	104	0.55	153	0.54
18	85–110 mm	18	0.37	16	85–110 mm	78	0.49	96	0.47
	110–130 mm	12	0.50		110–130 mm	6	0.73	18	0.56
	Total	154	0.34		Total	85	0.53	342	0.42
19–23 Oct 92	45–60 mm	44	0.31	14–18 Dec 92	45–60 mm	—	—	44	0.31
	60–70 mm	68	0.48		60–70 mm	—	—	68	0.48
	70–85 mm	25	0.26		70–85 mm	60	0.32	85	0.30
22	85–110 mm	6	0.12	20	85–110 mm	68	0.43	74	0.36
	110–130 mm	8	0.33		110–130 mm	6	0.73	14	0.44
	Total	151	0.34		Total	134	0.38	285	0.35
16–23 Nov 92	45–60 mm	29	0.21	11–15 Jan 93	45–60 mm	—	—	29	0.21
	60–70 mm	36	0.25		60–70 mm	—	—	36	0.25
	70–85 mm	28	0.29		70–85 mm	84	0.45	112	0.39
26	85–110 mm	10	0.21	24	85–110 mm	56	0.35	66	0.32
	110–130 mm	7	0.29		110–130 mm	4	0.49	11	0.34
	Total	110	0.24		Total	144	0.41	254	0.32
14–18 Dec 92	45–60 mm	15	0.11	15–19 Feb 93	45–60 mm	—	—	15	0.11
	60–70 mm	39	0.27		60–70 mm	—	—	39	0.27
	70–85 mm	20	0.21		70–85 mm	52	0.28	72	0.25
30	85–110 mm	13	0.27	29	85–110 mm	38	0.24	51	0.25
	110–130 mm	4	0.17		110–130 mm	2	0.24	6	0.19
	Total	91	0.20		Total	92	0.26	183	0.23
11–15 Jan 93	45–60 mm	24	0.17	15–19 Mar 93	45–60 mm	—	—	24	0.17
	60–70 mm	23	0.16		60–70 mm	—	—	23	0.16
	70–85 mm	20	0.21		70–85 mm	19	0.10	39	0.14
34	85–110 mm	6	0.12	34	85–110 mm	19	0.12	25	0.12
	110–130 mm	6	0.25		110–130 mm	1	0.12	7	0.22
	Total	79	0.18		Total	39	0.11	118	0.15

Table 5 (continued)

Collection date (weeks after release)	Size at release	Total recap. *n*	% recapt.	Collection date (weeks after release)	Size at release	Total recap. *n*	% recapt.	Grand total	Grand total % recap.
Spring release				**Summer release**					
15–19 Feb 93	45–60 mm	19	0.14	12–16 Apr 93	45–60 mm	—	—	19	0.14
	60–70 mm	36	0.25		60–70 mm	—	—	36	0.25
	70–85 mm	23	0.24		70–85 mm	12	0.06	35	0.12
39	85–110 mm	6	0.12	38	85–110 mm	4	0.03	10	0.05
	110–130 mm	5	0.21		110–130 mm	1	0.12	6	0.19
	Total	89	0.20		Total	17	0.05	106	0.13
15–19 Mar 93	45–60 mm	5	0.04						
	60–70 mm	13	0.09						
	70–85 mm	4	0.04						
45	85–110 mm	1	0.02						
	110–130 mm	2	0.08						
	Total	25	0.06						
12–16 Apr 93	45–60 mm	2	0.01						
	60–70 mm	8	0.06						
	70–85 mm	3	0.03						
47	85–110 mm	—	—						
	110–130 mm	—	—						
	Total	13	0.03						
Totals	45–60 mm	195	1.39	Totals	45–60 mm	—	—	195	1.39
(weeks 3–39)	60–70 mm	453	3.19	(weeks 3–38)	60–70 mm	—	—	453	3.19
	70–85 mm	373	3.90		70–85 mm	650	3.44	1,023	3.60
	85–110 mm	185	3.83		85–110 mm	631	4.00	816	3.96
	110–130 mm	80	3.35		110–130 mm	37	4.51	117	3.64
Grand totals (through week 39)		1,286	2.86			1,318	3.72	2,604	3.23

earlier studies with July releases; and 2) the late-summer decline in abundance resulted in less reduction in release impact in 1992 than in other years.

Recapture rates were disproportionately higher in this study than after releases in 1990 and 1991 (Table 6). Number of fish released at Kahaluu Stream in 1992 exceeded the number released at that same site in 1990 and 1991 by 690% and 180%, respectively. Yet the total number of fish recaptured from week 16 on exceeded comparable data (similar sampling effort) from 1990 and 1991 by 1,560% and 420%, respectively (Table 6). Increase in the effectiveness of 1992 releases is revealed by comparing recapture frequencies (no. recaptured/ no. released) and by including data from all release sites. From week 16 on, 1.65% of the cultured mullet released in 1992 were recaptured in cast-net samples. This recapture rate was 6 times that seen in the 1990 study (0.28%) and 1.7 times the rate in the 1991 study. Sampling frequency and number of cast-net samples were nearly identical among the three studies.

These differences among studies were statistically significant. Recapture rates after 1992 releases were significantly greater than expected in all pair-wise comparisons of 1992 data with data from 1990 and 1991 (Table 6; *G*-tests, $P<0.001$ in all cases). The 1991 study yielded significantly greater recapture rates than did the 1990 study, when fish released outside of the Kahaluu site in 1990 are included in the comparison (Table 6; all sites, $\chi^2 = 225$, $P<0.001$).

Discussion

Marine enhancement potential

Context of this study A rigorous test of marine stock-enhancement involves several phases of research. These are considered here to place the current study in perspective. Key research phases include 1) understanding both wild stock distribution

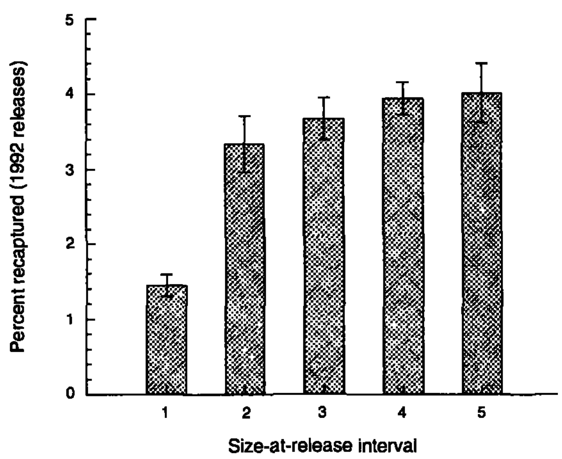

Figure 5

Recapture frequencies ([number recaptured/number released] × 100% [±SEM]) of cultured striped mullet juveniles released in 1992 and subsequently collected over 11 months at four nursery habitats in Kaneohe Bay. Combined data for fish from both spring and summer releases (n=6 lots) are presented and compared over the five size-at-release intervals: interval 1 = 45–60 mm, 2 = 60–70 mm, 3 = 70–85 mm, 4 = 85–110 mm, and 5 = 110–130 mm total length.

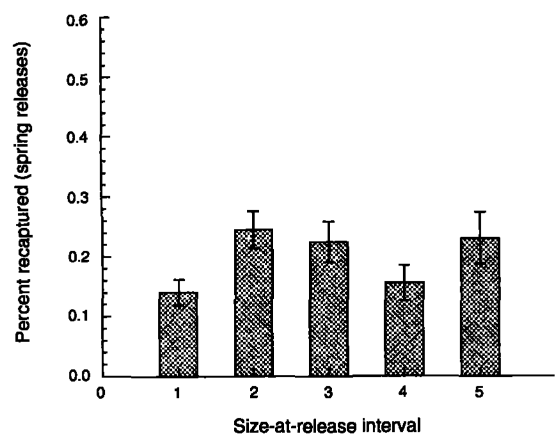

Figure 6

Recapture frequencies ([number recaptured/number released] × 100% [± SEM]) following spring releases (n=3 lots) of cultured striped mullet juveniles in 1992. These are combined data from four nursery habitats sampled in Kaneohe Bay. Data are plotted against size-at-release intervals, which are explained in the legend for Figure 5. Data are for the period from 16 weeks after release through the end of the study.

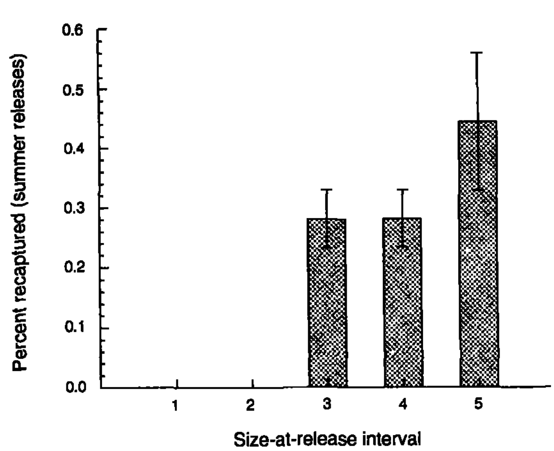

Figure 7

Recapture frequencies ([number recaptured/number released] × 100% [± SEM]) following summer releases (n=3 lots) of cultured striped mullet juveniles released in 1992. Size-at-release intervals are explained in Figure 5. No fish in the two smallest intervals were released in summer 1992. Data from the four nursery habitats are combined and are for the period from 16 weeks after release through the end of the study.

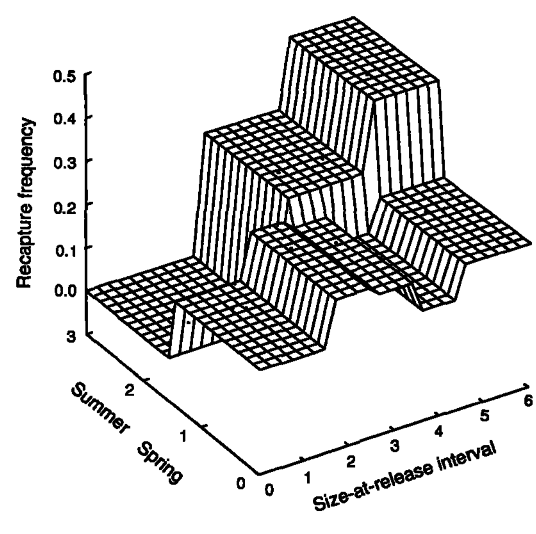

Figure 8

Comparison of spring and summer recapture frequencies of cultured striped mullet for the period from 16 weeks after release through the end of the study. No fish in the two smallest size intervals were released in summer. Data from the four nursery habitats are combined. Size-at-release intervals are explained in Figure 5.

and abundance patterns as well as behavior and ecological interactions; 2) conserving wild stock genetics and health; 3) developing reliable culture techniques; 4) establishing and testing a tagging method to identify hatchery fish; 5) evaluating optimal release strategies through experimentation; 6) assessing hatchery-release effect on population size and fishery landings; and 7) modeling economic costs and benefits (Richards and Edwards, 1986; Shaklee et al., 1993). These issues are interrelated to some degree (Blankenship and Leber, 1995).

That cultured fish will survive in the wild and contribute to stock abundance is a basic assumption that should be tested early in the development stage of planned hatchery-release programs (Richards and Edwards, 1986), notwithstanding the need to consider fish genetics and health, as well as economics of the fishery. In coastal ecosystems, understanding the potential of stock enhancement involves at least four levels of investigation in order to quantify growth

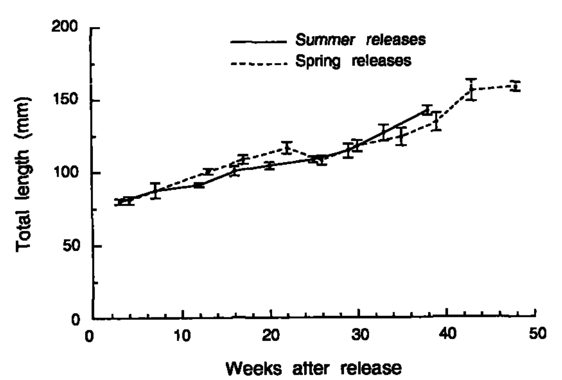

Figure 9

Mean total length (±SEM, n=3 lots) of cultured striped mullet released at 70–85 mm TL in spring and summer 1992 and retrieved in net samples over the next 10 to 11 months.

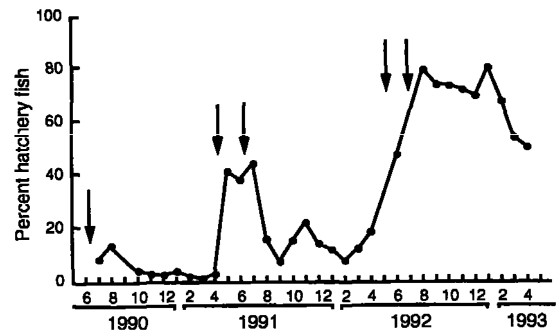

Figure 10

Percent contribution of cultured striped mullet to total abundance (wild and cultured striped mullet) in cast-net samples over a three-year study period in Kaneohe Bay (including this study). Data are from monthly cast-net collections at Kahaluu Stream. Arrows identify release periods. Spring and summer releases were conducted in 1991 and 1992. Releases in 1990 were made only in summer. Numbers on x-axis represent months of the year.

Table 6

Summary of numbers of cultured mullet released and recapture frequencies in Kaneohe Bay following hatchery releases in 1990, 1991, and 1992. Chi-square values (χ^2) and probablity levels (P) from G-tests are given for pair-wise comparisons of recapture frequencies (1990 vs. 1991 and 1991 vs. 1992). There were two release sites in Kaneohe Bay in 1990 and 1991.

	Kahaluu Stream			All sites combined		
	1990	1991	1992	1990	1991	1992
Released						
Total tagged	11,676	45,790	80,507	42,822	91,245	80,507
Recaptured						
Total	177	952	2,632	227	2,405	2,632
% recovered	1.52	2.08	3.27	0.62	2.64	3.27
χ^2		16.0	148		689	56
P		<0.001	<0.001		<0.001	<0.001
Total after 16 wk	85	315	1,326	118	890	1,326
% recovered	0.73	0.69	1.65	0.28	0.96	1.65
χ^2		0.021	225		225	147
P		>0.640	<0.001		<0.001	<0.001

and survival of cultured fish in the wild, each focused on different life stages:

Level 1 **Initial recapture rate:** A key issue is whether a release-recapture design is adequate to evaluate stocking effectiveness. Initial sampling of released fish after a pilot release (e.g. during the first couple of months) will establish whether monitoring is feasible under the chosen release strategies (e.g. release habitat, fish size at release) and with the condition of released fish and sampling design. An early look at recapture rates reveals a maximum expected recapture rate for a particular release (which will likely decrease over time because of mortality and dispersal) and can help determine whether release strategy or sampling strategy needs to be redesigned.

Level 2 ***Growth, survival and impact on abundance through the nursery stage of the life cycle:*** Assessing comparative effectiveness of release strategies in increasing juvenile recruitment can provide an early indication of enhancement potential. Two corollaries of the enhancement concept should be considered here: the first—cultured fish survive, grow, and contribute to population size—cannot be evaluated meaningfully without information on how chosen release strategies affect postrelease survival; the second corollary—cultured fish do not displace wild stocks—can be evaluated experimentally, once dispersal patterns are understood (Leber et al., 1995).

Level 3 **Growth, survival, and release impact through asymptotic growth:** involves assessment of release impact on adult population size and fishery landings. Recapture rates and growth can also be modeled to evaluate enhancement potential (Polovina, 1990, 1991). Results gained at level 2 on release-strategy impacts on survival may need to be confirmed at this level (e.g. a collecting gear bias favoring smaller fish can mask a size-at-release impact on survival at level 2; Leber et al., in press; Leber and Arce, in press).

Level 4 **Impact on reproduction and recruitment in subsequent generations:** With genetic markers to track hatchery impact across generations, an assessment can be made of hatchery impact on production of the next generation (Jørstad et al., 1994a).

Criteria for success need to be specified as testable hypotheses in enhancement programs (Larkin, 1979; Peterman, 1991; Blankenship and Leber, 1995). Percent increase in fish population size needed for success will depend on fish species and enhancement objectives. Cost-benefit evaluations can help determine yields required to break even. But value can be subjective and difficult to quantify when the objective is to enhance a recreational fishery or a threatened or endangered species. We evaluated success in terms of impact on recruitment and improvement in recapture rate in this study compared with our earlier studies. Our data reveal how information from pilot studies can be used to identify effective release strategies. Break-even costs for striped mullet enhancement are considered elsewhere (Leber and Cantrell[5]).

Enhancement concept with striped mullet In this paper, we address level 2 above and reveal a substantial hatchery contribution in nursery habitats following releases of cultured mullet. Results of this study corroborate the first corollary of the marine stock enhancement concept, that released fish can survive, grow, and contribute to recruitment. Released juveniles integrated with wild mullet at primary nursery habitats in Kaneohe Bay. Cultured mullet were abundant in samples on every collection date over the 11 months. Cultured fish showed linear growth; those released in May 1992 doubled in size within 48 weeks, with growth rates similar to wild striped mullet (Leber et al., in press). The second corollary, that cultured mullet are not displacing wild mullet at the Kahaluu Stream release site, was experimentally evaluated and corroborated in a follow-up field experiment (Leber et al., 1995).

Hatchery effect on abundances in nursery habitats was remarkable after adjusting release strategy to incorporate findings from pilot releases in Kaneohe Bay. Except for anadromous fishes, there are very few examples where hatchery releases have revealed the potential to double juvenile recruitment success with a marine organism (e.g. Kristiansen and Svåsand, 1990, for cod; Kitada et al., 1992, for flounder; Honma, 1993, for scallops). Cultured fish released in this study increased recruitment of juvenile striped mullet at the release site in 1992 by at least 100%. This large effect was partly a function of a poor recruitment year for wild fish and was partly due to higher survival following summer releases, compared with survival in earlier studies (Leber, 1995; Leber et al.[3]). Release impact on abundance

[5] Leber, K. M., and R. N. Cantrell. 1996. Effect of fish size-at-release on the relative cost to enhance striped mullet in Hawaii. In review.

was also considerable in streams 3 km away from the release site. Decrease in proportions of cultured fish in samples after 8 months coincided with the seasonal period (March) when yearlings begin to move out of nursery habitats into deeper water and when new recruits begin to arrive (Major, 1978; Leber, 1995; Oceanic Institute[4]).

The striped mullet collected in this study that were released in 1991 (Leber et al.[3]) represented a large portion (28%) of the total striped mullet caught in net samples at Kaneohe Stream. These data document that a portion of the cultured striped mullet released in Kaneohe Bay can be found in their nursery habitats up to two years after release.

It is evident from this study and from follow-up creel interviews in which fishery landings were surveyed that there is significant potential to increase the striped mullet population in Kaneohe Bay with relatively small-scale hatchery releases. Cultured mullet released in spring 1992 were first detected in the commercial fishery in Kaneohe Bay in October 1993, when a 367-mm-TL fish was recovered during contact interviews with commercial fishermen (Leber and Arce, in press). By the seasonal closure of the fishery in December 1994, 119 of the mullet released in 1992 had been recovered through contact interviews with commercial fishermen. According to tag data from interviewing fishermen in Kaneohe Bay, fish released in this study accounted for 9% of the commercial catch during fall 1994, at which time the proportion of cultured fish to wild fish was increasing logarithmically. Ninety-four of the cultured fish caught were checked for maturity; 44 males were ripe with milt and 2 females were gravid with mature eggs (Leber and Arce, in press).

Survival and hatchery impact on abundance The best gauge of the immediate effect of the 1992 hatchery releases on mullet population size is actual abundance of released fish in the wild. But actual number of survivors after 11 months is unknown. The >50% hatchery contribution to abundance at the release site is impressive, but from an economic viewpoint, data on actual increases in yields and population size are needed to compare the benefits of enhancement with costs. An estimate of survival would be a better gauge of stock-enhancement impact than would the proportion of hatchery fish in the population.

However, it is logistically difficult to quantify actual survival of released cultured fishes in open coastal environments. There is substantial literature on evaluating animal survival, much of which is based on change in relative abundance (catch per unit of effort [CPUE]) over time in mark-release-recapture experiments. The analysis theory for release-recapture experiments dates back to Ricker's (1945, 1948) relative recovery-rate method. A more general theory based on maximum likelihood was developed independently by Seber (1970) and Youngs and Robson (1975). Brownie et al. (1985) and Burnham et al. (1987) have provided a detailed discussion of maximum-likelihood methods. These methods for estimating survival are based on change in abundance in samples over time and are confounded in open environments by dispersal into and out of the population (Connor et al., 1983; MacCall, 1990; Nichols and Pollock, 1990; Frank, 1992) and by gear bias, as capture probabilities change with changes in fish size and habitat selection (e.g. Kjelson and Colby, 1976; MacLennan, 1992; Thompson, 1994; Acosta and Appeldoorn, 1995; Leber et al., in press). Without reliable estimates of immigration and emigration, one can use change in capture rate over time to measure loss from a population (i.e. the sum of mortality + emigration) but not to estimate mortality alone.

In this study, decrease in abundance over time in cast-net samples is a poor indicator of actual survival. Striped mullet move out of their nursery habitats as they approach maturity (Blaber, 1987), and juveniles move from shallow water to deeper water during their first year (Major, 1978; Leber et al.[3]). Overall decline in mullet abundance in samples over the 11-month study period was due to a combination of mortality, dispersal, and gear bias as mullet grew and moved into deeper water where cast nets are not effective sampling devices.

Postrelease mortality prior to initial sampling is also a source of error in estimating survival following hatchery releases. A key question is whether mortality of cultured fish is intense during the first day or so after a release (e.g. what percent of released individuals are consumed by predators?). Initial mortality could be an important factor in enhancement dynamics and should be accounted for in survival estimates, especially in open environments where mortality can be confused with emigration. But initial postrelease mortality has received little attention in "release-recapture" literature. There is evidence, however, that until cultured fish have been conditioned by exposure to predators in the wild, inadequate predator avoidance behavior can result in increased mortality (Parker, 1968; Healey, 1982; Olla and Davis, 1988; Olla and Davis, 1989; Tsukamoto, 1993; Olla et al., 1994). Initial mortality following hatchery releases of Pacific salmon can be severe and is most intense during the 48-h period following releases.[6] Ini-

[6] Blankenship, H. L. 1995. Washington Department of Fish and Wildlife, 600 Capitol Way North, Mail Stop 43149, Olympia, WA. Personal commun.

tial behavior of stocked fish can also be directly affected by handling stress and temperature change, either of which could cause an increase in susceptibility to predators shortly after release (Fuiman and Ottey, 1993).

The difficulty in quantifying initial mortality is in obtaining an unbiased early sample of abundance to establish a baseline recapture rate for comparison with recapture rates in later samples. Dispersal of striped mullet from the point of release is not an immediate event (Leber et al., personal observ.). The first few hours after a release should be the very time when released fish are most vulnerable to predators. However, immediate sampling in an open environment to determine initial abundance in samples violates assumptions of basic mark-recapture models (Ricker, 1975), primarily the assumption that marked fish mix randomly within the study area.

Without a reliable, unbiased method to estimate postrelease survival in open coastal ecosystems, how do we gauge benefits from hatchery releases? In effect, the best indicator of hatchery impact is total annual catch of cultured fish in a fishery. Thus, assessment of marine stock enhancement requires unbiased estimates of CPUE, total fishing effort, and proportion of cultured fish in the fishery. Accurate catch statistics for marine organisms are expensive and often lacking (e.g. Shomura[7]), as in Hawaii for striped mullet. The difficulty of assessing total hatchery impact is exacerbated when cultured fish are released unmarked, which has often been the case with marine fishes (discussed in Richards and Edwards, 1986).

Because a fishery on juveniles is lacking, some measures besides fishery landing statistics are needed to evaluate survival of cultured fish during the nursery phase. Consequently, researchers in coastal systems report recovery rates and percent cultured fish in samples of cultured and wild fish (hatchery contribution) as early indicators of enhancement effect. Percentage of cultured fish can be a good relative indicator of release impact but only when reported with CPUE for wild and cultured fish. Hatchery contribution is a function of abundance of wild fish, release magnitude, survival, dispersal, size of hatchery and wild fish, and environmental carrying capacity.

Hatchery contribution is sensitive to variation in any of the above six factors. Thus, alone, it has low information content as an indicator of success. In fact, year to year comparisons of hatchery contribution can be misleading. Three examples below illustrate the relationship among hatchery contribution (%C), CPUE of cultured (C) and wild fish (W) in samples, and actual hatchery effect on recruitment:

Example 1 %C in year 1 and year 2 are equal, but W is greater in year 2: hatchery effect on magnitude of recruitment actually increased; increase is not apparent from comparing %C but is when C and W are compared between years;

Example 2 %C is greater in year 2 but W is less: actual hatchery effect on abundance could be identical in years 1 and 2;

Example 3 %C and W are both greater in year 2: substantial increase in hatchery effect (i.e. greater hatchery impact than realized by merely comparing %C between years).

Lacking an unbiased indicator of actual survival following hatchery releases, we submit that recruitment, hatchery contribution, and recovery rate (no. captured/no. released) provide a good preliminary indication of enhancement effect if all three of these are presented. Each is needed to evaluate and control enhancement effectively.

Variation in fishery yields is driven largely by recruitment dynamics (see Frank and Leggett, 1994, for recent review). The CPUE of cultured and wild fish reflects the magnitude of recruitment, which should have a direct relevance to fishery yields, if food and habitat are available. Also, without CPUE data, there is no indication of how the whole population (cultured and wild individuals) is changing from year to year in response to natural recruitment processes, enhancement, and other management strategies.

Hatchery contribution from pilot studies can be used as an index to help in planning release magnitude at levels that would not swamp wild stocks with cultured fish. Hatchery contribution is easily computed from CPUE data (i.e. $\%C = [C \times 100\%] / [C + W]$).

Because cost effectiveness is directly related to survival of cultured fish in the wild, optimizing recovery rate should also be a key consideration in enhancement programs (Kitada et al., 1992). Recovery rate provides a relative measure of survival and is a good indicator (if standardized by sampling effort) for comparing performance of cultured fish. In comparisons of recovery rates from different years, differences in release magnitude are factored out.

The above three indicators can be used to evaluate release effects during the juvenile stage, before fish enter the fishery, to obtain a preliminary estimate of stock enhancement success. Thus, a way of

[7] Shomura, R. S. 1987. Hawaii's marine fishery resources: yesterday (1900) and today (1986). Honolulu Laboratory, Southwest Fisheries Center, Natl. Mar. Fish. Serv., Admin. Rep. H-87-21.

characterizing field data is needed that clearly reflects 1) recruitment (CPUE) of both cultured and wild fish, 2) hatchery contribution, and 3) standardized recovery rates for released fish. One way of illustrating these variables together is presented here.

All three indicators are used in Figure 11 to compare relative hatchery effect at Kahaluu in 1992 with data from three other years of pilot releases (Leber, 1995; Leber et al., 1995; Leber et al.[3]). Overall, CPUE of cultured juveniles was greatest after 1992 releases. However, recovery rate (and presumably survival) was greatest after 1993 releases. Thus, 1992 releases had greatest impact on recruitment, whereas yield per stocked juvenile was greatest from 1993 releases. Recovery rate improved in 1992 and again in 1993. The improvement was largely due to better survival after adjusting SAR protocol to avoid summer releases of fish <70 mm TL and to avoid release sites outside of habitat preferred by striped mullet. Although hatchery contribution was inflated in 1992 because of reduced recruitment of wild fish, overall effect from releasing cultured fish was greatest following 1992 releases, and recovery rate improved most in 1992.

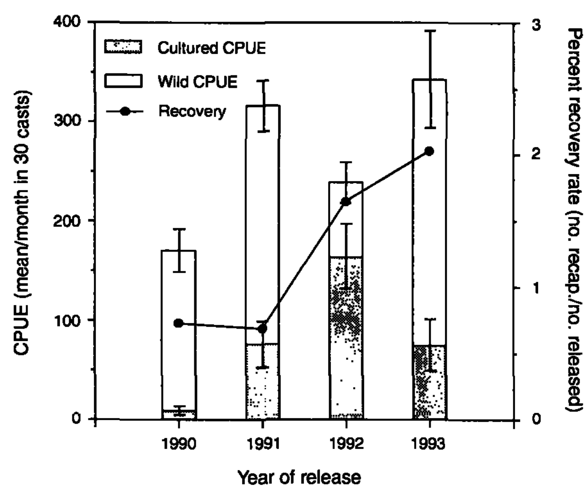

Figure 11

Stacked bar graph of release impact at Kahaluu Stream following releases conducted there from 1990 to 1993. CPUE is total number of cultured fish (gray bars) and wild fish (open bars) in 30 casts per month averaged over 10–11 monthly collections. Percent cultured fish (hatchery contribution) varied from monthly average of 4.4% (SEM =±1.3) of the striped mullet collected in 1990 to 20.6% (±4.1) in 1991, 65.2% (±5.2) in 1992, and 23.5% (±5.0) in 1993. Percent recovery rate of cultured fish (solid line with closed circles) is number recaptured/number released, × 100%.

Pilot releases

Whereas actual survival of cultured fish may be difficult to quantify in open ecosystems, relative survival can be quantified and compared across treatment groups in pilot release experiments (Burnham et al., 1987). Results from two previous years of pilot releases were used to identify optimal release strategies for this study. Discontinuing releases near the Hawaii Institute of Marine Biology (HIMB) pier after 1990 resulted in a >300% increase in recovery rate in the 1991 study; the increase in recovery rate was compounded in 1992 by modifying SAR protocol as well (Table 6; note the 1990 data in Fig. 11 are only for fish released at Kahaluu). By confining releases in this study to the vicinity of Kahaluu Stream and by adjusting minimum SAR upwards to include only fish >70 mm TL in summer, we achieved a 590% increase in recovery rate over the 1990 study and a 170% increase over the 1991 study (Table 6: after 16 weeks, all sites combined).

This study provided new information on effects of release site. Choice of release microhabitat at Kahaluu (inlet and upstream lagoon) affected dispersal north from Kahaluu into other streams but had no apparent impact on survival. The similar survival was surprising, given the poor survival in 1990 of fish released along the shoreline near HIMB pier, in comparison to fish released at streams (Leber, 1995; Leber and Arce, in press). We hypothesize that refuge from predators, afforded by mangroves and other shoreline vegetation in the north end of Kaneohe Bay, accounted for the higher survival of mullet that were released at Kahaluu Inlet and that dispersed along the shoreline.

Release microhabitat affected the extent of enhancement in Kaneohe Bay in this study by partially controlling colonization of nursery habitats north of Kahaluu. If a management objective for full-scale releases were to have a portion of fish from each release lot disperse into adjacent nursery sites in the bay (e.g. in order to maximize use of available nursery habitat), then releases at the inlet to Kahaluu Stream would achieve this. If stronger site fidelity were desired, releases farther upstream would result in lower dispersal during the nursery phase of the life cycle. The ability to affect which nursery habitats are selected by released fish, coupled with knowledge about recruitment success of wild fish, could be used to help prevent overstocking a particular nursery.

Implications

This study shows that information from pilot releases is critical for managing full-scale stock enhancement in coastal environments. The use of results from pilot studies to modify release protocol caused a considerable increase in recovery rates and hatchery contributions to striped mullet abundance in their nursery habitats. Even before fish enter a fishery, data on relative survival of juveniles following pilot releases can be used to design effective release strategies.

The results of this study could be magnified if enhancement activities expanded to include other nursery sites in Kaneohe Bay, provided sufficient habitat is available. Leber et al. (1995), reported hatchery releases of cultured striped mullet at Kahaluu had an additive effect on population size. Kahaluu, Kaalaea, and Waiahole streams are primary mullet nursery habitats in Kaneohe Bay; including the latter two with Kahaluu as release sites would increase stock-enhancement effect.

According to this study, Leber et al. (1995), and Leber and Arce (in press), marine stock enhancement appears to have high potential as an additional fishery management tool for Hawaiian coastal fishes. Hatchery releases of striped mullet could be used in conjunction with fishing regulations and habitat protection, with the expectation that recruitment success of juveniles and subadults would increase significantly in Kaneohe Bay. To ensure that stocks are actually enhanced by hatchery-release activities, information from pilot studies needs to be coupled with additional management considerations to provide a controlled approach to stock enhancement (Peterman, 1991; Cowx, 1994; Blankenship and Leber, 1995).

Acknowledgments

We thank Lee Blankenship and Dan Thompson from the state of Washington Department of Fish and Wildlife for their guidance and assistance in applying coded wire tags to striped mullet in this experiment. We thank Chris Kelley, Ryan Takushi, and biologists of the Oceanic Institute finfish program for their assistance with fish production, Anthony Morano (who assisted with tagging, field collections, and tag decoding) and Laurie Peterson for help with graphics. We also thank Lee Blankenship, Stan Moberly, Jeff Polovina, and Rich Lincoln for their ideas in many fruitful discussions about the need to quantify hatchery-release effects. Lastly, we thank Lee and Stan and three anonymous reviewers for their insightful comments on and improvements to the manuscript. This paper was funded by a grant from the National Oceanic and Atmospheric Administration.

Literature cited

Acosta, A. R., and R. S. Appeldoorn.
1995. Catching efficiency and selectivity of gill nets and trammel nets in coral reefs from southwestern Puerto Rico. Fish. Res. 22(3–4):175–196.

Anthony, V. C.
1993. The state of groundfish resources off the northeastern United States. Fisheries (Bethesda) 18(3):12–17.

Bannister, R. C. A., and A. E. Howard.
1991. A large-scale experiment to enhance a stock of lobster (*Homarus gammarus* L.) on the English east coast. ICES Mar. Sci. Symposia 192:99–107.

Barlow, C. G., and B. A. Gregg.
1991. Use of circuli spacing on scales to discriminate hatchery and wild barramundi *Lates calcarifer.* Aquacult. Fish. Manage. 22:491–498.

Bilton, H. T., D. F. Alderdice, and J. T. Schnute.
1982. Influence of time and size at release of juvenile coho salmon (*Oncorhynchus kisutch*) on returns at maturity. Can. J. Fish. Aquat. Sci. 39:426–447.

Blaber, S. J. M.
1987. Factors affecting recruitment and survival of mugilids in estuaries and coastal waters in Southeastern Africa. Am. Fish. Soc. Symp. 1:507–518.

Blankenship, H. L.
1990. Effects of time and fish size on coded wire tag loss from chinook and coho salmon. Am. Fish. Soc. Symp. 7:237–243.

Blankenship, H. L., and K. M. Leber.
1995. A responsible approach to marine stock enhancement. *In* H. L. Schramm Jr. and R. G. Piper (eds.), Uses and effects of cultured fishes in aquatic ecosystems. Am. Fish. Soc. Symp. 15:167–175.

Brownie, C., D. R. Anderson, K. P. Burnham, and D. S. Robson.
1985. Statistical inference from band recover data—a handbook, 2nd ed. U.S. Fish and Wildlife Serv. Resource Publ. 156, Washington, D.C.

Buckley, R. M., and H. L. Blankenship.
1990. Internal extrinsic identification systems: overview of implanted wire tags, otolith marks and parasites. Am. Fish. Soc. Symp. 7:173–182.

Burnham, K. P., D. R. Anderson, G. C. White, C. Brownie, and K. H. Pollock.
1987. Design and analysis methods for fish survival experiments based on release-recapture. Am. Fish. Soc. Monograph 5, Bethesda, MD.

Connor, E. F., S. H. Faeth, and D. Simberloff.
1983. Leafminers on oak: the role of immigration and in situ reproductive recruitment. Ecology 64:191–204.

Cowx, I. G.
1994. Stocking strategies. Fish. Manage. Ecol. 1:15–30.

Drawbridge, M. A., D. B. Kent, M. A. Shane, and R. F. Ford.
1995. The assessment of marine stock enhancement in southern California: a case study involving the white seabass. *In* H. L. Schramm Jr. and R. G. Piper (eds.), Uses and effects of cultured fishes in aquatic ecosystems. Am. Fish. Soc. Symp. 15:568–569.

FAO.
1992. Food and Agriculture Organization of the United Nations yearbook: fishery statistics 70 (1990). FAO, Rome.

Frank, K. T.
1992. Demographic consequences of age-specific dispersal in marine fish populations. Can. J. Fish. Aquat. Sci. 49:2222–2231.

Frank, K. T., and W. C. Leggett.
1994. Fisheries ecology in the context of ecological and evolutionary theory. Annu. Rev. Ecol. Syst. 25:401–422.

Fuiman, L. A., and D. R. Ottey.
1993. Temperature effects on spontaneous behavior of larval and juvenile red drum, *Sciaenops ocellatus*, and implications for foraging. Fish. Bull.. 91:23–35.

Grimes, C. B.
1995. Perspective of the AFS marine fishery section on uses and effects of cultured fishes in aquatic ecosystems. Am. Fish. Soc. Symp. 15:593–594.

Hager, R. C., and R. E. Noble.
1976. Relation of size at release of hatchery-reared coho salmon to age, size, and sex composition of returning adults. Prog. Fish-Culturist 38:144–147.

Healey, M. C.
1982. Juvenile Pacific salmon in estuaries: the life support system. *In* V. S. Kennedy (ed.), Estuarine comparisons, p. 315–341. Academic Press, New York, NY.

Honma, A.
1993. Aquaculture in Japan. Japan FAO Association, Tokyo, 98 p.

Iglesias, J., and G. Rodríguez-Ojea.
1994. Fitness of hatchery-reared turbot, *Scophthalmus maximus* L., for survival in the sea: first year results on feeding, growth and distribution. Aquacult. Fish. Manage. 25 (suppl. 1):179–188.

Jefferts, K. B., P. K. Bergman, and H. F. Fiscus.
1963. A coded-wire identification system for macroorganisms. Nature (London) 198:460–462.

Jørstad, K. E., O. I. Paulsen, G. Nævdal, and S. Thorkildsen.
1994a. Genetic studies of cod, *Gadus morhua* L., in Masfjorden, western Norway: comparisons between the local stock and released, artificially reared cod. Aquacult. Fish. Manage. 25 (suppl. 1):77–91.

Jørstad, K. E., G. Nævdal, O. I. Paulsen, and S. Thorkildsen.
1994b. Release and recapture of genetically tagged cod fry in a Norwegian fjord system. *In* A. R. Beaumont (ed.), Genetics and evolution of aquatic organisms, p. 519–528. Chapman and Hall, London, England.

Kent, D. B., M. A. Drawbridge, and R. F. Ford.
1995. The roadblocks and milestones to making marine stock enhancement work: perspectives from the middle of a twenty-year program in southern California. *In* H. L. Schramm Jr. and R. G. Piper (eds), Uses and effects of cultured fishes in aquatic ecosystems. Am. Fish. Soc. Symp. 15:492–498.

Kitada, S., K. Hiramatsu, and H. Kishino.
1994. Estimating mortality rates from tag recoveries: incorporating over-dispersion, correlation and change points. ICES Mar. Sci. Symposia 51:241–251.

Kitada, S., Y. Taga, and H. Kishino.
1992. Effectiveness of a stock enhancement program evaluated by a two-stage sampling survey of commercial landings. Can. J. Fish. Aquat. Sci. 49:1573–1582.

Kjelson, M. A., and D. R. Colby.
1976. The evaluation and use of gear efficiencies in the estimation of estuarine fish abundance. *In* M. Wiley (ed.), Estuarine processes, Vol. 2, p. 416–424. Academic Press, New York, NY.

Kristiansen, T. S., and T. Svåsand.
1990. Enhancement studies of coastal cod in western Norway. Part III: Interrelationships between reared and indigenous cod in a nearly land-locked fjord. J. Int. Counc. Explor. Sea 47:23–29.

Larkin, P. A.
1979. Maybe you can't get there from here: a foreshortened history of research in relation to management of Pacific salmon. J. Fish. Res. Board Can. 36: 98–106.
1993. The year 2000, will we be ready technically? We're ready, already. Fisheries (Bethesda) 18(3):6–11.

Leber, K. M.
1995. Significance of fish size-at-release on enhancement of striped mullet fisheries in Hawaii. J. World Aquacult. Soc. 26:143–153.

Leber, K. M., and S. M. Arce.
In press. Stock enhancement effect in a commercial mullet, *Mugil cephalus* L., fishery in Hawaii. Fish. Manage. Ecol. 3.

Leber, K. M., N. P. Brennan, and S. M. Arce.
1995. Marine enhancement with striped mullet: Are hatchery releases replenishing or displacing wild stocks? *In* H. L. Schramm Jr. and R. G. Piper (eds.), Uses and effects of cultured fishes in aquatic ecosystems, 376–387. Am. Fish. Soc. Symp. 15.

Leber, K. M., D. A. Sterritt, R. N. Cantrell, and R. T. Nishimoto.
In press. Contribution of hatchery-released striped mullet, *Mugil cephalus*, to the recreational fishery in Hilo Bay, Hawaii. *In* K. Lowe (ed.), Proceedings of the first biennial symposium for the Main Hawaiian Islands marine resources investigation. Tech. Rep. 96–01. Hawaii Department of Land and Natural Resources, Division of Aquatic Resources, Honolulu, HI.

MacCall, A. D.
1990. Dynamic geography of marine fish populations. Univ. Washington Press, Seattle, 153 p.

MacLennan, D. N.
1992. Fishing gear selectivity: an overview. Fish. Res. 13:201–204.

Major, P. F.
1978. Aspects of estuarine intertidal ecology of juvenile striped mullet, *Mugil cephalus*, in Hawaii. Fish. Bull. 76:299–314.

New, M. B.
1991. Turn of the millennium aquaculture: navigating troubled waters or riding the crest of the wave? World Aquacult. Soc. 22:28–49.

Nichols, J. D., and K. H. Pollock.
1990. Estimation of recruitment from immigration versus in situ reproduction using Pollock's robust design. Ecology 71:21–26.

Nordeide, J. T., J. H. Fosså, A. G. V. Salvanes, and O. M. Smedstad.
1994. Testing if year-class strength of coastal cod, *Gadus morhua* L., can be determined at the juvenile stage. Aquacult. Fish. Manage. 25 (suppl. 1):101–116.

NMFS.
1991. Our living oceans: first annual report on the status of U.S. living marine resources. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/SPO-1, 123 p.
1992. Our living oceans: report on the status of U.S. living marine resources 1992. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/SPO-2, 148 p.

Olla, B. L., and M. Davis.
1988. To eat or not be eaten. Do hatchery-reared salmon need to learn survival skills? Underwater Naturalist 17:16–18.
1989. The role of learning and stress in predator avoidance of hatchery-reared coho salmon (*Oncorhynchus kisutch*) juveniles. Aquaculture 76:209–214.

Olla, B. L., M. W. Davis, and C. H. Ryer.
1994. Behavioral deficits in hatchery-reared fish: potential effects on survival following release. Aquacult. Fish. Manage. 25 (suppl. 1):19–34.
Parker, R. R.
1968. Marine mortality schedules of pink salmon of the Bella Coola River, Central British Columbia. J. Fish. Res. Board Can. 25:757–794.
Peterman, R. M.
1991. Density-dependent marine processes in North Pacific salmonids: lessons for experimental design of large-scale manipulations of fish stocks. ICES Mar. Sci. Symp. 192:69–77.
Polovina, J. J.
1990. Application of yield-per-recruit and surplus production models to fishery enhancement through juvenile releases. *In* A. Sparks (ed.), Marine farming and enhancement, p. 29–33. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 85.
1991. Evaluation of hatchery releases of juveniles to enhance rockfish stocks with application to Pacific Ocean perch *Sebastes alutus*. Fish. Bull. 89:129–136.
Richards, W. J., and R. E. Edwards.
1986. Stocking to restore or enhance marine fisheries. *In* R. H. Stroud (ed.), Fish culture in fisheries management, p. 75–80. Am. Fish. Soc., Bethesda, MD.
Ricker, W. E.
1945. Abundance, exploitation, and mortality of the fishes of two lakes. Invest. Indiana Lakes Streams 2:345–448.
1948. Methods of estimating vital statistics of fish populations. Indiana Univ. Publications in Science Series 15, 401 p.
1969. Food from the sea. *In* Resources and man, p. 87–108. W.H. Freeman and Co, San Francisco, CA.
1975. Computation and interpretation of biological statistics of fish populations. Department of the Environment, Fisheries and Marine Service, Fish. Res. Board Can. Bull. 191, Ottawa, Canada.
Schnute, J. T., and L. J. Richards.
1994. Stock assessment for the 21st century. Fisheries (Bethesda) 19(11):10–16.
Seber, G. A. F.
1970. Estimating time-specific survival and reporting rates for adult birds from band returns. Biometrika. 57:313–318
Shaklee, J. B., C. A. Busack, and C. W. J. Hopley.
1993. Conservation genetics programs for Pacific salmon at the Washington Department of Fisheries: living with and learning from the past, looking to the future. *In* K. L. Main and E. Reynolds (eds.), Selective breeding of fishes in Asia and the United States, p. 110–141. The Oceanic Institute, Honolulu, HI.
Sissenwine, M. P., and A. A. Rosenberg.
1993. Marine fisheries at a critical juncture. Fisheries (Bethesda) 18(10):6–14.
Sokal, R. R., and F. J. Rohlf.
1981. Biometry. W.H. Freeman, San Francisco, CA.
Smedstad, O. M., A. G. V. Salvanes, J. H. Fosså, and J. T. Nordeide.
1994. Enhancement of cod, *Gadus morhua* L., in Masfjorden: an overview. Aquacult. Fish. Manage. 25 (suppl. 1):117–128.
Solemdal, P., D. Dahl, D. S. Danielssen, and E. Moksness.
1984. The cod hatchery in Flodevigen—background and realities. *In* E. D. Dahl, D. S. Danielssen, E. Moksness, and P. Solemdal (eds.), The propagation of cod, *Gadus morhua* L., p. 17–45. Flodevigen Rapportserie, Flodevigen.
Stoner, A. W.
1994. Significance of habitat and stock pre-testing for enhancement of natural fisheries: experimental analysis with queen conch *Strombus gigas*. J. World Aquacult. Soc. 25:155–165.
Støttrup, J. G., J. R. Nielsen, C. Krog, and K. Rasmussen.
1994. Results on the extensive production of North Sea cod, *Gadus morhua* L., and their growth and distribution subsequent to release in Limfjord, Denmark. Aquacult. Fish. Manage. 25 (suppl. 1): 143–160.
Svåsand, T. and T. S. Kristiansen.
1990. Enhancement studies of coastal cod in western Norway. Part IV: Mortality of reared cod after release. J. Int. Counc. Explor. Sea 47:30–39.
Svåsand, T., K. E. Jørstad, and T. S. Kristiansen.
1990. Enhancement studies of coastal cod in western Norway. Part 1: Recruitment of wild and reared cod to a local spawning stock. J. Int. Counc. Explor. Sea 47:5–12.
Svåsand, T., K. E. Jørstad, G. Blom, and T. S. Kristiansen.
1991. Application of genetic markers for early life history investigations on Atlantic cod (*Gadus morhua* L.). ICES Mar. Sci. Symposia 192:193–199.
Thompson, G. G.
1994. Confounding of gear selectivity and the natural mortality rate in cases where the former is a nonmonotone function of age. Can. J. Fish. Aquat. Sci. 51:2654–2664.
Tsukamoto, K.
1993. Marine fisheries enhancement in Japan and the quality of fish for release. Eur. Aquacult. Soc. Special Publ. 19, 556 p.
Tsukamoto, K., H. Kuwada, J. Hirokawa, M. Oya, S. Sekiya, H. Fujimoto, and K. Imaizumi.
1989. Size-dependent mortality of red sea bream, *Pagrus major*, juveniles released with fluorescent otolith-tags in News Bay. J. Fish Biol. 35:59–69.
Wilkinson, L.
1990. SYSTAT: the system for statistics. SYSTAT, INC., Evanston, IL, 676 p.
Willis, S. A., W. W. Falls, C. W. Dennis, D. E. Roberts, and P. G. Whitchurch.
1995. Assessment of season-of-release and size-at-release on recapture rates of hatchery-reared red drum (*Sciaenops ocellatus*) in a marine stock enhancement program in Florida. *In* H. L. Schramm Jr. and R. G. Piper (eds.), Uses and effects of cultured fishes in aquatic ecosystems. Am. Fish. Soc. Symp. 15:354–365.
WRI (World Resources Institute).
1990. World resources 1990–91. Oxford Univ. Press, New York, NY.
Youngs, W. D., and D. S. Robson.
1975. Estimating survival rate from tag returns: model tests and sample size determination. J. Fish. Res. Board Can. 32:2365–2371.