American Fisheries Society Symposium 15:376–387, 1995

Marine Enhancement with Striped Mullet: Are Hatchery Releases Replenishing or Displacing Wild Stocks?

KENNETH M. LEBER, NATHAN P. BRENNAN, AND STEVE M. ARCE

The Oceanic Institute, Makapuu Point
Waimanalo, Hawaii 96795, USA

Abstract.—The hypothesis that marine hatchery releases can increase fish abundances has at least two corollaries that need to be tested: (1) cultured fish can survive and grow when released into coastal environments; and (2) cultured fish do not displace wild individuals. Both are being tested in Hawaii. The present study was conducted to evaluate whether hatchery releases of striped mullet *Mugil cephalus* actually increase abundances or displace wild stock. In summer 1993, 5,811 wild striped mullet were captured, tagged, and released in three lots back into two primary nursery habitats in Kaneohe Bay. Three weeks later, quantitative sampling with cast nets was conducted in several striped mullet nursery habitats within the bay to evaluate pretreatment dispersal of wild fish. Following those initial collections, cultured striped mullet were released to establish the primary treatment condition, a hatchery release. A total of 29,354 cultured striped mullet were tagged and released, but at only one of the nursery sites (treatment site). Monthly monitoring was conducted over an 8-month period to determine if there was greater dispersal of wild fish at the treatment site. There was no significant difference in the dispersal rates of wild fish from the treatment site compared with the control (no hatchery release) site. As expected, based on earlier pilot hatchery releases, a majority of tagged and released cultured and wild striped mullet remained within those nursery habitats where they were released.

Hatchery releases in this study did not result in displacement of wild individuals from the principal nursery habitat in Kaneohe Bay. The cultured fish released there increased abundances of striped mullet at the treatment site by around 33%. Thus it appears that even small-scale releases could help replenish the depleted striped mullet fishery in Kaneohe Bay; conducting small-scale hatchery releases in several nursery habitats in Kaneohe Bay should increase overall striped mullet abundances in this estuary. This study also corroborated earlier experiments in Hawaii showing a direct relationship between fish size at release and recapture rate.

These results indicate hatchery releases can increase abundances of targeted inshore fish populations in Hawaii. If a careful approach is used, marine stock enhancement appears to have considerable potential as an additional fishery management tool.

World fishery resources currently face enormous risk of severe depletion. As capture fisheries continue to be exploited at a nonsustainable pace (NOAA 1991, 1992) and as human population size doubles by the middle of the next century (FAO 1992), what will become of today's fisheries? Will commercial fishing virtually pass from existence in the next 50 years? Will recreational angling be an option for coastal residents? Hardin's (1968) "tragedy of the commons" holds that our public resources will eventually be squandered if their fate is left in the hands of user groups.

Current fisheries management practices have been generally ineffective at stemming overexploitation. Better control over fishing effort is clearly needed (Coutin and Payne 1989; Ross and Nelson 1992). It is also clear that habitat degradation is a major factor in the decline of coastal organisms (Moyle et al. 1992; Bryan et al. 1992).

Lacking a direct responsibility for protecting fisheries resources, public response will likely continue to be apathetic towards the hard choices that are needed to reduce fishing effort and restore critical habitat. Limited entry to fisheries and subsequent ownership of those fisheries by a select few has been considered as a management alternative (Fox 1992). Political reality, however, has prevented widespread use of this concept. Containing development in coastal habitats could become more acceptable if the steady loss of wilderness and recreation areas leads to public discontent.

The two current methods of managing coastal fisheries, control of fishing effort and habitat protection (including pollution control), might be augmented by an additional management strategy to help prevent further depletions and extinctions. Recent research suggests that propagation and release (stock enhancement) of marine organisms has potential to increase population abundances in coastal environments (Tsukamoto et al. 1989; Svasand et al. 1990; Honma 1993; Kent et al. 1995, this volume; Willis et al. 1995, this volume; Leber, in press;

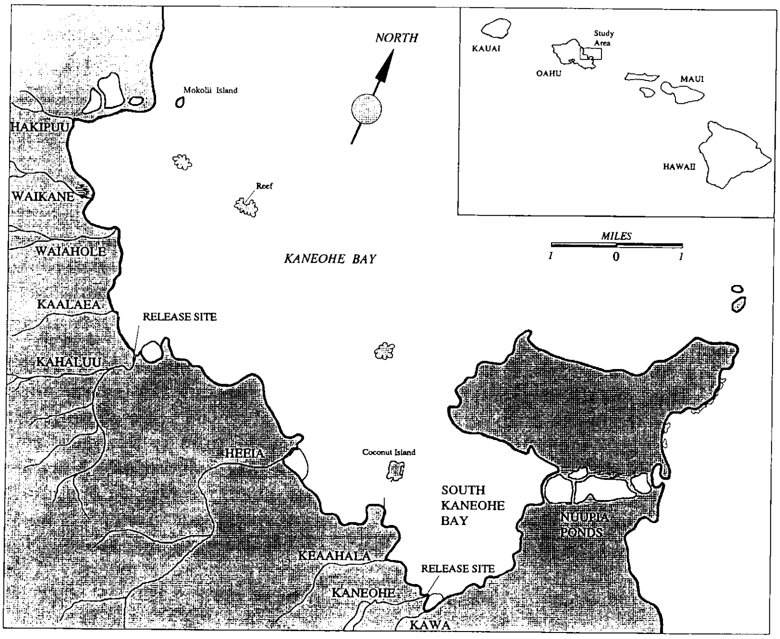

FIGURE 1.—Map of the study area in Kaneohe Bay. Control fish (wild striped mullet) were released near the mouth of Kaneohe stream, and treatment fish (wild striped mullet at treatment site) and cultured fish were released near the mouth of Kahaluu stream. Recapture collections were conducted at release sites and neighboring streams in Kaneohe Bay (Kaneohe, Keaahala, Kahaluu, Kaalaea, and Waiahole streams).

Leber et al., in press). Despite over 50 years of marine hatchery releases, serious effort at evaluating the potential of coastal stock enhancement has come about during only the past 10 years (see Stroud 1986). To realize the full potential of marine enhancement to help conserve and replenish rapidly declining stocks, we must develop this technology carefully and quickly (Blankenship and Leber 1995, this volume).

The central issue that needs resolution in marine stock enhancement is the hypothesis that hatchery releases can actually increase population size of a variety of coastal species. Two important and largely untested predictions underlie this hypothesis—the first is that significant numbers of hatchery fish can survive in the wild; the second is that released hatchery fish actually increase abundances rather than displace wild stocks.

Both of these predictions are being tested in Hawaii with two inshore fishes, striped mullet *Mugil cephalus* and *Polydactylus sexfilis*. Previous experiments have documented that cultured striped mullet can survive in the wild. Juvenile cultured striped mullet regularly exceed 20% of the striped mullet collected in quantitative samples in striped mullet nursery habitats 6 to 8 months after small-scale pilot releases (Leber, in press; Leber et al., in press). Pilot releases of juveniles in Hilo Bay, Hawaii, also contribute around 20% of the catch in the recreational pole and line fishery (Leber et al., in press). The results of an experiment to evaluate whether such hatchery releases supplement or displace wild striped mullet in Kaneohe Bay, the largest estuary in Hawaii, are presented here.

Methods

A factorial-design, release–recapture experiment was performed to test the effects of the release of juvenile cultured striped mullet on the dispersal of existing wild striped mullet juveniles in the estuaries of Kaneohe Bay, Hawaii. In June–July 1993, 5,811 wild striped mullet fingerlings were captured, tagged, and released at two of the most productive nursery habitats in Kaneohe Bay—Kaneohe stream and Kahaluu stream (Figure 1). The release of tagged wild fish provided baseline data on the dispersal patterns of wild striped mullet before and after releasing cultured striped mullet. In August 1993, approximately 4 weeks after the wild releases, 29,354 hatchery fish were tagged and released into Kahaluu stream (treatment site) to establish the primary treatment condition. No cultured fish were released at Kaneohe stream (control site).

Wild striped mullet juveniles were collected during a peak recruitment period, from 1 June through 21 June, at Kaneohe stream and Kahaluu lagoon. To increase the total number of wild striped mullet fingerlings tagged and released in this study, additional collections were conducted at neighboring striped mullet nursery habitats within Kaneohe Bay.

Beach seines were used to capture wild striped mullet. Fish were caught in seines, transferred into 1,000-L hauling tanks, and transported by truck to The Oceanic Institute. Upon arrival, the wild striped mullet were transferred to 40,000-L quarantine tanks where they recovered from handling stress.

After quarantine procedures were completed, the wild striped mullet fingerlings were graded into four size-classes ranging in total length (TL) from 45 mm to 110 mm (45 to 60 mm; 60 to 70 mm; 70 to 85 mm; and 85 to 110 mm). The striped mullet were then tagged with binary coded wire tags (CWT; Northwest Marine Technology, Inc., Olympia, Washington) to identify fish origin (wild), initial capture site, size at release, release site (Kaneohe stream or Kahaluu stream), and release lot (date). Buckley and Blankenship (1990) and Bergman et al. (1992) discuss the utility of the CWT for marking fishes. The tags were implanted in cartilaginous tissue in the snout by use of an automatic tag injector equipped with head molds designed specifically for striped mullet by researchers from the State of Washington Department of Fish and Wildlife.

A total of 5,811 wild striped mullet were released in 3 replicate lots at Kahaluu stream and Kaneohe stream on 25 June, 30 June, and 2 July 1993. Numbers released per lot were kept as similar as possible. Releases at the control site and treatment site were conducted on the same day, 3–4 hours apart, for each lot. The wild fish were released about 4 weeks prior to releases of cultured fish.

Cultured striped mullet were reared at The Oceanic Institute. Striped mullet broodstock were spawned throughout the winter of 1993. Hatched striped mullet were reared through mid-August to fingerlings for tagging and release. Larval striped mullet were hatched and cultured in 5,000-L, round, conical-bottom tanks for 45 d. Stage-one juveniles, 45 d old and 20 mm TL, were transferred to 8,000-L round tanks and nursed for an additional 40 d until stage-two juveniles (85 d old and 40 mm TL). Stage-two juveniles were transferred to 30,000-L round tanks and nursed to the sizes released in this study (60 to 130 mm TL). In culture tanks, juvenile striped mullet growth rates averaged 0.5 mm/d.

Cultured striped mullet were graded into four size-classes ranging from 60 mm to 130 mm TL (60 to 70 mm; 70 to 85 mm; 85 to 110 mm; and 110 to 130 mm). The fish were provided a 2-d period to recover from grading stress, then tagged with CWTs. Batch codes were used to identify fish type (cultured), size at release, release site (Kahaluu stream), and release lot.

A CWT retention rate of 97% has been documented over a 12-month period for striped mullet (Oceanic Institute 1991). To verify tag retention rates in this study, at least 5% of the fish tagged for each release site were randomly subsampled from each release lot. The subsamples totaled 307 tagged wild fish and 1,533 tagged cultured fish, which were retained in tanks for up to 6 months for periodic tag retention checks. The subsampled fish were not released.

Previous studies have shown a direct relationship between striped mullet size at release and survival following summer releases in Kaneohe Bay (Leber, in press). Those data were used to target sizes for release of cultured fish during this study. Mostly large stage-two juveniles (70 to 130 mm TL) were released at the treatment site, Kahaluu stream.

A total of 29,354 cultured striped mullet juveniles were tagged and released. The replicate lots were released over a 3 week period, on 30 July, 6 August, and 13 August 1993. Due to a shortage of cultured striped mullet ranging in size from 70 to 110 mm TL for the final release lot, that lot was supplemented with 3,852 tagged striped mullet from a smaller size-class (60 to 70mm TL).

All releases were conducted during midday or early afternoon. Successive release lots spanned tide ranges from low to high. At the release sites, salinities at the top of the water column ranged from 0 to 5‰, whereas salinities at the bottom ranged from 20 to 32‰ (Table 1). Releases were conducted near the shoreline in water from 0.5 to 1.5 m deep.

Releases of wild striped mullet at the control site, Kaneohe stream, were conducted approximately 200 m upstream from the stream mouth. At the treatment site, Kahaluu stream, all releases were conducted within a lagoon, approximately 300 m upstream from the stream mouth. Both of the release sites are primary striped mullet nursery habitats in Kaneohe Bay (Oceanic Institute 1991). Kahaluu stream is located on the north end of Kaneohe Bay (Figure 1). This tributary is fed by

TABLE 1.—Environmental conditions at release sites and in the transport tanks during each release.

Variable	Kaneohe stream (wild striped mullet release)			Kahaluu stream (wild striped mullet release)			Kahaluu stream (cultured striped mullet release)		
	Lot 1[a]	Lot 2[a]	Lot 3[a]	Lot 1[a]	Lot 2[a]	Lot 3[a]	Lot 1[b]	Lot 2[b]	Lot 3[b]
Field conditions									
Salinity (‰)									
Top	2	5	5	5	5	5	0	0	4
Bottom	32	32	32	29	29	26	20	30	23
Water temperature (°C)									
Top	26	27	26	29	32	30	31	27	25
Bottom	28	28	27	31	30	29	27	26	26
Dissolved oxygen (mg/L)									
Top		7.5	7.8		8.2	8.5	6.8	7.2	8.8
Bottom		5.6	5.5		3.8	6.0	6.2	3.2	3.9
Secchi disk depth (cm)									
Top	65	80	65	25	80	65	70	70	90
Bottom	70	80	85	75	105	105	115	75	115
Tide (cm)									
Stage	Low	Incoming	Incoming	Incoming	Outgoing	High	Incoming	Low	High
Height	18.3	61	36.6	21.4	51.9	67.1	64.1	24.4	64.1
Weather									
Cloud cover	60%	20%	70%	100%	30%	10%	70%	100%	100%
Condition		Trades	Trades	Breezy	Calm	Windy		Rain	Rain
Loading time	1100	1015	1020	1100	1445	1405	1100	1030	1100
Release time	1152	1120	1122	1445	1550	1510	1240	1230	1220
Transfer tank conditions									
Salinity (‰)	23	20	19	23	20	16	23	21	18.5
Dissolved oxygen (mg/L)									
Beginning	6.5	7.6	8.2	6.5	7.5	7.9	7.6	10.3	7.7
Ending	12.8	8.3	10.6	8.4	7.9	8.1	5.6	8.7	8.2
Water temperature (°C)									
Beginning	25.5	26.0	27.0	26.0	26.0	25.0	25.8	25.0	24.5
Ending	26.0	26.0	27.0	26.0	26.0	26.0	25.0	26.7	25.0

[a]Release dates were lot 1, 25 June; lot 2, 30 June; and lot 3, 2 July 1993.
[b]Release dates were lot 1, 30 July; lot 2, 6 August; and lot 3, 13 August 1993.

several stream systems that originate in the Koolau mountain range. The mouth of Kaneohe stream lies 11.6 km south of the Kahaluu stream mouth in South Kaneohe Bay.

To evaluate the effect of hatchery-released fish and to compare growth and survival of tagged wild fish with cultured fish, monthly collections were made with cast nets in several Kaneohe Bay nursery habitats. Monitoring began on 19 July 1993, 2 1/2 weeks after the last of the wild striped mullet releases, to establish initial dispersal patterns of wild fish before cultured striped mullet were released. Sampling during the post-treatment period began on 23 August 1993, 10 d after releasing the last lot of cultured fish. Each field collection was done over a 5-d period. There were 8 monthly collections.

Sampling design included collections at five nursery sites within Kaneohe Bay. The sites were Kaneohe stream (control site), Keaahala stream (1.1 km north of Kaneohe stream), Kahaluu stream (treatment site; 11.6 km north of Kaneohe stream), Kaalaea stream (12.6 km north of Kaneohe stream), and Waiahole stream (15 km north of Kaneohe stream). Collections were made during the day over an 8-h period at each sampling station. All collection sites were established in the vicinity of documented primary nursery habitats for striped mullet (Oceanic Institute 1991).

To standardize sampling effort, two substations were established at each station—one upstream, the other near the stream mouth. Within substations, 15 cast-net throws were made. Thus, a total of 150 cast-net samples were taken each month. To broaden the range of microhabitats and fish size

TABLE 2.—Summary statistics for 3,619 wild stripped mullet released into Kaneohe stream (control site) and 2,192 wild stripped mullet released into Kahaluu stream (treatment site). Beginning one month later, 29,354 cultured striped mullet were released at the treatment site to evaluate the effect of hatchery releases on dispersal of wild juveniles. All individuals were identified using coded wire tags.

Size (mm)	Wild fish Lot[a] 1	Wild fish Lot[a] 2	Wild fish Lot[a] 3	Wild fish Total (*N*)	Cultured fish Lot[b] 1	Cultured fish Lot[b] 2	Cultured fish Lot[b] 3	Cultured fish Total (*N*)
				Kaneohe stream				
45–60	519	512	821	1,852				
60–70	356	340	380	1,076				
70–85	204	193	197	594				
85–110	11	47	39	97				
110–130								
Total (*N*)	1,090	1,092	1,437	3,619				
				Kahaluu stream				
45–60	468	227	0	695				
60–70	218	216	166	600			3,852	3,852
70–85	312	312	171	795	4,977	5,015	1,386	11,378
85–110	38	36	28	102	3,014	3,019	2,158	8,191
110–130					2,012	1,982	1,939	5,933
Total (*N*)	1,036	791	365	2,192	10,003	10,016	9,335	29,354

[a]Release dates were lot 1, 25 June; lot 2, 30 June; and lot 3, 2 July 1993.
[b]Release dates were lot 1, 30 July; lot 2, 6 August; and lot 3, 13 August 1993.

ranges sampled, two different size cast nets were used. Of the 15 casts per substation, 10 were conducted with a 5-m-diameter, 10-mm-mesh net, and 5 casts were made with a 3-m-diameter, 6.5-mm-mesh net. The smaller net was more effective in narrow upstream habitats.

Placement of cast nets was stratified over schools of striped mullet juveniles, rather than completely random. Random sampling yielded few wild striped mullet and very few tagged individuals. Striped mullet schooled in fairly low densities within the clear-water nursery habitats, and collections targeted these schools. Nevertheless, the data used to determine recapture rates, hatchery contribution rates, and proportions of tagged wild or cultured striped mullet in samples were randomly distributed, because we had no indication that schools, once sighted, contained tagged individuals.

Striped mullet sampled in these collections were measured and checked for tags by means of a portable tag detector (Northwest Marine Technology, Inc.). Tagged striped mullet were placed on ice and returned to the laboratory at The Oceanic Institute to be weighed and measured. Tags were extracted using a binary search to locate them within the snout region. Tag codes were read using a binocular microscope (40 × magnification). Less than 1% of the tags from recaptured fish were lost during extraction. To verify tag codes, each was read twice (once each by two different research assistants).

Data were analyzed using Systat (Wilkinson 1990). A randomized-block-design analysis of variance (ANOVA) was used to compare means. Treatments (fish type, release site, and fish size at release) were blocked over time (3 release lots). Proportions were arcsine transformed. Systat Basic was used to write tag decoding algorithms. For each recaptured fish, the algorithms identified fish type, place of origin, size at release, release site, release date, release lot, and number of fish released per treatment–lot combination, based on the binary tag codes. An error check algorithm was also used. Variance estimates are expressed throughout as standard errors.

Results

Release Statistics

After releasing 5,811 tagged wild striped mullet by early July at the control and treatment sites (Kaneohe and Kahaluu streams), 29,354 tagged cultured juvenile striped mullet were released at the treatment site in August to establish the primary treatment effect (hatchery release). Numbers of tagged and released fish varied among size groups. An attempt was made to keep numbers similar (within experimental groups) from lot to lot (Table 2).

To establish and acclimate identifiable wild fish at both the treatment and control sites, plans called for releasing at least 1,000 tagged wild fish in each

TABLE 3.—Total numbers of wild and cultured striped mullet recovered in cast-net samples at the release sites following releases at Kahaluu stream (treatment site) and Kaneohe stream (control site). Wild fish were tagged and released at Kahaluu and Kaneohe streams in July. Cultured fish were released at Kahaluu stream in August. The percentages of total fish recovered that were cultured fish are given.

	1993						1994		
Fish recovered	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Total
				Kahaluu stream					
Wild fish recovered									
Total (*N*)	440	372	192	323	107	167	360	77	2,038
Tagged (*N*)	23	15	9	17	14	11	16	1	106
Cultured fish recovered									
Total (*N*)		224	49	64	12	37	75	62	523
Percent		37.6	20.3	16.5	10.1	18.1	17.2	44.6	
				Kaneohe stream					
Wild fish recovered									
Total (*N*)	232	53	58	110	13	142	96	102	806
Tagged (*N*)	62	5	5	14	1	21	11	10	129
Cultured fish recovered									
Total (*N*)				2					2
Percent				1.8					

of three release lots approximately 1 month prior to the release of cultured fish. However, because of difficulties inherent in capturing and holding wild fish, that target was achieved in only four of the six release lots. Only one-third of the 1,000 wild individuals targeted were available for the 2 July release at the treatment site.

All wild fish released at the treatment site were initially collected at that site. However, because of difficulties in collecting sufficient numbers of wild juveniles at the control site, 86% of the fish released at the control site were initially captured either at Waiahole stream or outside Kaneohe Bay. To evaluate any effect this may have had on dispersal from the control site, all tagged wild fish were coded to identify initial capture site in addition to the primary coding variables. Capture site had an insignificant effect on dispersal (*G*-test = 1.01, df = 1, $P = 0.31$).

Tag retention for cultured fish ($N = 1{,}533$) and wild fish ($N = 307$) subsampled across release lots averaged 98.1% (±0.9%) and 99.3% (±0.7%), respectively, after 75 d. With one exception (93.9%), tag-retention rates within all release lots exceeded 96%.

Recapture Summary

At least 596 tagged cultured fish were recaptured in monthly cast-net collections made in striped mullet nursery habitats over the 7-month period following their release. Based on the average 98.4% tag retention rate, the number of cultured fish sampled can be extrapolated as 607, or 2.1% of the cultured fish released. Seven tags (0.8%) were lost during the retrieval and reading process and thus are not included in this analysis.

Of the wild striped mullet tagged and released at the control site (control fish), 145 (4.0%) were recaptured in cast-net samples over the 8-month study period following their release. Of the wild fish released at the treatment site (treatment fish), 108 (4.9%) were recaptured during the same (8-month) period.

Numbers of tagged fish retrieved at the release sites decreased after 1 month postrelease (Table 3), but were fairly constant during the remainder of the study. Wild striped mullet were clearly more abundant at the treatment site. The total number of tagged wild fish recaptured was greatest at the control site (Kaneohe stream), which was expected because more wild fish were tagged and released there. However, this pattern varied considerably from month to month. Nearly one-half of the tagged wild fish recaptured at the control site were sampled within 30 d after their release; experimental wild fish were more abundant at the treatment site in five of the seven remaining collections.

Recaptured cultured fish constituted up to 44% of the total striped mullet in monthly samples at the treatment site (mean = 25.7 ± 4.8%, $N = 7$ collection dates). Only 2 cultured fish were recaptured at the control site. After an initial decline in abundance, cultured fish clearly became established at the treatment site, where they persisted in samples through the end of the study (Table 3).

Effect of Hatchery Releases on Wild Striped Mullet

Pretreatment comparison of dispersal patterns.—Collections made in five nursery habitats in July 1993 revealed initial dispersal patterns of the wild fish released a month earlier. Because those collections were conducted prior to the primary treatment effect, the hatchery release in August, they established a control condition for examining hatchery-release effect.

There was little movement away from release sites prior to the release of hatchery fish. There was no significant difference in mean percent dispersal of treatment fish, compared with control fish, out of release habitats and into adjacent streams in July (Figure 2; ANOVA, $P > 0.18$, df = 2, $N = 3$ release lots). Data in Figure 2 are mean percent per lot of total fish recaptured within experimental treatment groups in July. Proportions of treatment and control fish recaptured at the sites where they were released also were not significantly different (ANOVA, $P > 0.49$, df = 2, $N = 3$). No treatment fish were collected outside the treatment site in July. However, five of the control fish collected in July had dispersed outside the control site; three of those had moved 12 km and were caught at the treatment site. Although this shows a trend towards slight movement out of the control site, this difference between treatment and control fish was trivial. Combining data from the 3 lots within treatments, 100% of the treatment fish and 92.5% of the control fish recaptured in July were collected at the site where they were released.

Post-treatment comparison of dispersal patterns.—Following the release of nearly 30,000 cultured fish at the treatment site in August, there was no trend towards greater dispersal of wild fish from the treatment site than from the control site (Figure 3; ANOVA, $P > 0.80$, df = 2, $N = 3$). The data plotted in Figure 3 are mean percent per lot ($N = 3$) of the total fish recaptured within treatment groups after the hatchery release. Summing across lots within treatments, 97.7% of the 85 treatment fish sampled from August 1993 through February 1994, and 85.9% of the 78 control fish sampled, were collected at the site where they were released.

Cultured striped mullet also showed a tendency to remain in the vicinity of the release site (Figure 3). Only 12.2% of cultured fish recaptured had dispersed away from the treatment site. A total of 523 cultured fish were recaptured at the treatment site, an average of 25.7% of the total striped mullet collected there.

There was a clear trend towards less movement of the wild treatment fish than of the control fish from their respective release sites through the end

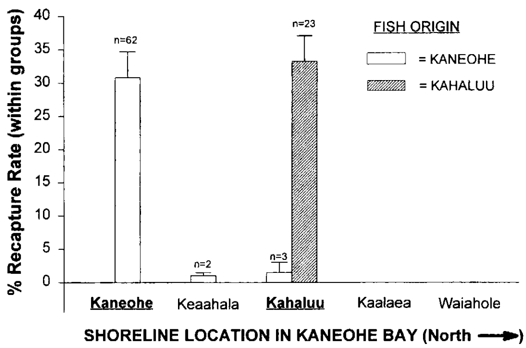

FIGURE 2.—Pretreatment dispersal patterns of tagged wild striped mullet by release location. Mean percent recaptured (per lot, within treatment groups) is shown with standard errors for wild fish released at the control site, Kaneohe stream (control fish) and wild fish released at the treatment site, Kahaluu stream (treatment fish). Wild fish were initially recaptured 2.5 weeks following the collection, tagging, and release of 5,811 wild juveniles at the control and treatment sites in July 1993.

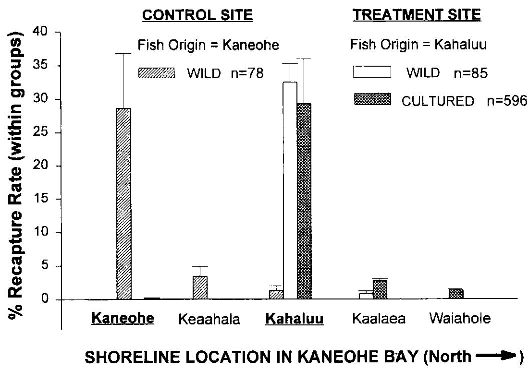

FIGURE 3.—Post-treatment dispersal patterns of wild and cultured striped mullet from release sites. Mean percent recaptured (per lot, within treatment groups) is shown with standard errors for control fish, wild fish released at the treatment site (treatment fish), and cultured fish released at the treatment site. Post-treatment collections began about 3 weeks after tagging and release of 29,354 cultured fish into Kahaluu stream.

of 1993 (Table 4). There was also clear movement of a portion of the cultured fish out of the treatment site and into two streams to the north. Cultured fish were consistently recaptured both at and outside the release site. With the exception of the November samples from Waiahole stream, cultured fish were always collected at Kaalaea and Waiahole streams as well as at the treatment site, Kahaluu stream.

A comparison of the relative contribution of monthly collections to total tagged wild fish caught within treatments reveals another similarity. Monthly fluctuations in recapture rates were nearly identical for treatment and control fish collected at release sites from month 2 on (Figure 4). After the first month in the wild, proportions were evenly distributed in collections over time. For wild treatment fish, no single collection dominated. Cultured fish were more similar to control fish, for which total recaptures were dominated by the number sampled during the first month after release (Table 4).

After analyzing these data, we noted that recapture rates of the treatment fish approached zero in February 1994 (month 8, Figure 4). To evaluate whether this was a sampling artifact, or a permanent decline in wild fish at the treatment site, we conducted an additional standard cast-net collection at Kahaluu stream in April 1994. The April collection yielded 155 striped mullet, of which 64 were tagged. Of the tagged fish, there were 8 wild and 56 cultured striped mullet. Thus, the low frequency of treatment fish in month 8 samples reflected natural sampling variability, as seen with control fish in month 5 (Figure 4).

Size-Specific Survival

The effect of fish size at release (SAR) on recapture rates was examined to evaluate whether hatchery releases at the treatment site affected size-specific survival rates of wild fish. Fish SAR had a clear effect on survival of cultured fish (Figure 5). Although four size-classes of cultured striped mullet were tagged and released (Table 2), the smallest size range released (SAR group 2, 60 to 70 mm TL) were prevalent in samples only during initial collections. By the last 2 months of the study, recapture rates were clearly a direct function of SAR, and proportions of fish that ranged from 60 to 85 mm TL at release (SAR groups 2 and 3) were underrepresented in samples.

Comparison of size-specific recapture rates of treatment fish, before versus after release of hatchery fish, revealed no significant differences in sur-

TABLE 4.—Dispersal patterns of 5,811 wild striped mullet released into Kaneohe Bay and then sampled in cast-net collections, both before and after releases of 29,354 cultured striped mullet into Kahaluu stream (treatment site) in August 1993. Dispersal of Kaneohe stream (control site) was used in both pretreatment and post-treatment collections to establish a control pattern. Data are mean (SE) number of individuals per release lot ($N = 3$) retrieved in 30 cast-net samples, July 1993–February 1994. Streams are sorted north to south.

Collection period and recapture site	Number of tagged wild fish recaptured		Number of tagged cultured fish recaptured
	Control fish	Treatment fish	
	Pretreatment		
19–23 Jul			
Waiahole	0 (0)	0 (0)	
Kaalaea	0 (0)	0 (0)	
Kahaluu	1.0 (1.0)	7.7 (.9)	
Keaahala	0.7 (0.3)	0 (0)	
Kaneohe	20.7 (2.6)	0 (0)	
	Post-treatment		
23–27 Aug			
Waiahole	0 (0)	0 (0)	1.7 (.9)
Kaalaea	0 (0)	0 (0)	4.7 (1.8)
Kahaluu	0.3 (.3)	5.0 (1.5)	74.7 (5.4)
Keaahala	0.7 (0.7)	0 (0)	0 (0)
Kaneohe	1.7 (0.3)	0 (0)	0 (0)
20–24 Sep			
Waiahole	0 (0)	0 (0)	0.7 (0.3)
Kaalaea	0 (0)	0.3 (.3)	0.7 (0.3)
Kahaluu	0.3 (0.3)	3.0 (1.0)	16.3 (3.9)
Keaahala	0.7 (0.3)	0 (0)	0 (0)
Kaneohe	1.7 (0.3)	0 (0)	0 (0)
18–22 Oct			
Waiahole	0 (0)	0 (0)	0.7 (0.3)
Kaalaea	0 (0)	0 (0)	1.0 (0.6)
Kahaluu	0.3 (0.3)	5.7 (1.5)	21.3 (11.1)
Keaahala	0.0 (0.0)	0 (0)	0 (0)
Kaneohe	4.7 (1.9)	0 (0)	0.7 (0.7)
18–24 Nov			
Waiahole	0 (0)	0 (0)	0 (0)
Kaalaea	0 (0)	0 (0)	0.7 (0.3)
Kahaluu	0 (0)	4.7 (2.2)	4.0 (0.6)
Keaahala	0.7 (0.3)	0 (0)	0 (0)
Kaneohe	0.3 (0.3)	0 (0)	0 (0)
13–17 Dec			
Waiahole	0 (0)	0 (0)	1.0 (1.0)
Kaalaea	0 (0)	0.3 (0.3)	3.7 (1.9)
Kahaluu	0 (0)	3.7 (0.7)	12.3 (5.2)
Keaahala	0.7 (0.3)	0 (0)	0 (0)
Kaneohe	7.0 (1.0)	0 (0)	0 (0)
10–14 Jan			
Waiahole	0 (0)	0 (0)	3.3 (0.3)
Kaalaea	0 (0)	0 (0)	1.0 (0.6)
Kahaluu	0 (0)	5.3 (.9)	25.0 (9.6)
Keaahala	0 (0)	0 (0)	0 (0)
Kaneohe	3.7 (3.2)	0 (0)	0 (0)
7–11 Feb			
Waiahole	0 (0)	0 (0)	0.3 (0.3)
Kaalaea	0 (0)	0 (0)	4.3 (1.3)
Kahaluu	0 (0)	0.3 (0.3)	20.7 (7.8)
Keaahala	0 (0)	0 (0)	0 (0)
Kaneohe	3.3 (1.2)	0 (0)	0 (0)

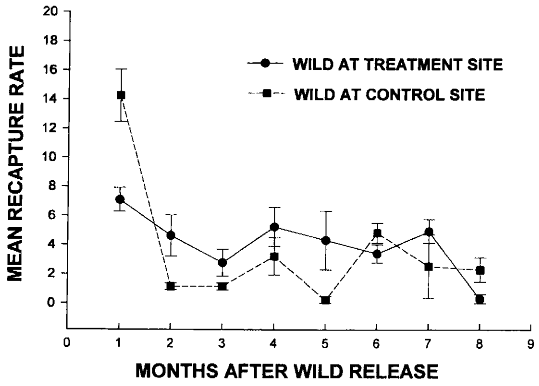

FIGURE 4.—The mean percent recaptured (within treatment groups) with standard errors for wild striped mullet released at the treatment site (Kahaluu stream) and wild fish released at the control site (Kaneohe stream) over the 8 months following the release of tagged wild fish.

vival patterns. Four size-classes of wild fish were released (SAR groups 1 through 4). Note that no wild fish in the 110 to 130 mm bracket, the largest group of cultured fish released, were captured and released. Treatment and control fish from the smallest size groups released (SAR groups 1 and 2, 45 to 70 mm TL) were frequently encountered in

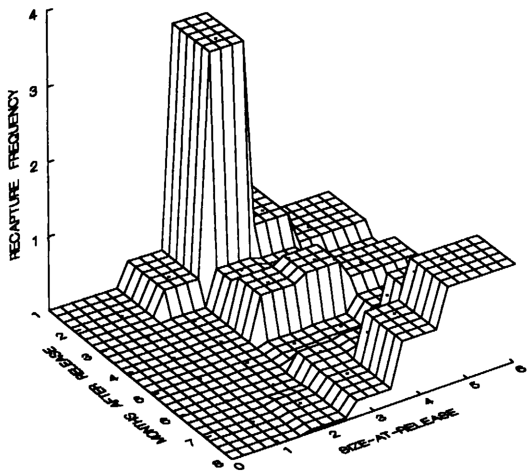

FIGURE 5.—Size-at-release effect on recapture rates of cultured striped mullet collected in cast-net samples at the treatment site, Kahaluu stream. Data are given for each of five size-classes (1 = 45–60 mm total length; 2 = 60–70 mm; 3 = 70–85 mm; 4 = 85–110 mm; and 5 = 110–130 mm). Data are percent recaptured of the total fish released per size interval. No cultured fish smaller than 60 mm were released.

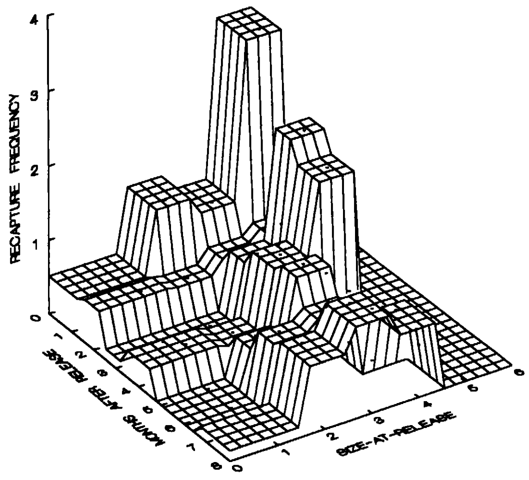

FIGURE 6.—Size-at-release effect on recapture rates of tagged wild striped mullet recaptured in cast-net samples at the treatment site, Kahaluu stream. Data are given for each of five size-classes (1 = 45–60 mm total length; 2 = 60–70 mm; 3 = 70–85 mm; 4 = 85–110 mm; and 5 = 110–130 mm). Data are percent recaptured of the total fish released per size interval. No wild striped mullet larger than 110 mm were released.

samples throughout the study (Figures 6 and 7). Wild fish were less affected by SAR than were cultured fish. The relationship between SAR and recapture rates for treatment fish was similar to that for control fish.

Discussion

Dispersal of wild striped mullet at the treatment site (treatment fish) was clearly unaffected by the release of cultured striped mullet. There was slight movement of treatment fish after the hatchery release in August, but there was also even greater movement of control fish out of the control site during that period.

The data within individual collections reveal that there was no hatchery release effect on recapture rates of wild fish. Had the hatchery fish displaced wild fish, we would have expected higher proportions of treatment fish outside the release habitat. This was not the case. Only two (2.4%) of the treatment fish that were recaptured after the hatchery release in August were collected outside the release site. In contrast, 15% of the control fish and 12.2% of the cultured fish sampled after the hatchery release were collected outside their respective release sites. Had the treatment fish moved from Kahaluu stream, they would have been picked up

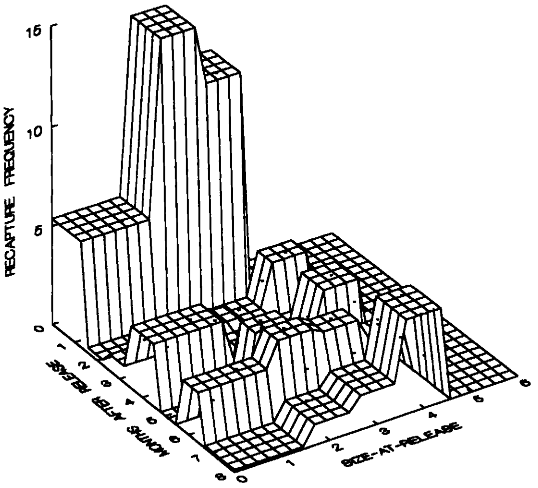

FIGURE 7.—Size-at-release effect on recapture rates of tagged wild striped mullet recaptured in cast-net samples at the control site, Kaneohe stream. Data are given for each of five size-classes (1 = 45–60 mm total length; 2 = 60–70 mm; 3 = 70–85 mm; 4 = 85–110 mm; and 5 = 110–130 mm). Data are percent recaptured of the total fish released per treatment group. No wild striped mullet larger than 110 mm were released.

elsewhere. This is supported by the fact that cultured fish moved out of Kahaluu stream and were subsequently sampled in adjacent streams during every collection period (Table 4). This same pattern was also evident in previous releases of cultured fish in Kaneohe Bay in 1990, 1991, and 1992 (Leber, in press; Leber, unpublished data). This study documents that Kahaluu stream, an important striped mullet nursery in Kaneohe Bay, could support a moderate hatchery release of around 30,000 striped mullet in addition to the wild juveniles already present in that nursery system at the time of the hatchery release.

The greater dispersal of wild fish from the control site may be related to the fact that wild fish were brought into the control site from other collection sites. Although most of the released fish that dispersed from the control site were originally captured elsewhere, G-test results indicated that differences in dispersal between striped mullet introduced from other streams and resident striped mullet could be explained by chance. Also, if the fish brought into the control site were dropped from this analysis, dispersal patterns of the treatment and control fish would be virtually identical.

As expected, based on previous studies in Hawaii (Leber, in press; Leber et al., in press) fish SAR had a marked effect on recapture rates of cultured striped mullet in this study. Survival of cultured striped mullet in the previous studies was directly related to SAR and was particularly poor for the smallest individuals released (45 to 60 mm TL). A similar, but less pronounced, trend was evident in this study for tagged wild fish. This trend was more pronounced at the treatment site. All sizes of wild fish released were represented in samples from both release sites throughout the study. Thus, cultured striped mullet did not appear to affect size-selective survival of wild fish.

Size at release is likely a principal mechanism controlling survival of cultured marine fish released into the wild. Although this relationship has been recognized with salmonids and other freshwater fishes, it has only recently been investigated with marine organisms. In addition to the Hawaiian studies, SAR effect has been shown for other marine fishes including madai *Pagrus major* in Japan (Tsukamoto et al. 1989; referred to as red sea bream by Tsukamoto), Atlantic cod *Gadus morhua* in Norway (Svasand and Kristiansen 1990), white seabass *Atractoscion nobilis* in California (Drawbridge et al., this volume), and red drum *Sciaenops ocellatus* in Florida (Willis et al., this volume).

Cultured fish averaged 25% of the total striped mullet collected monthly. This hatchery release increased striped mullet abundance at Kahaluu by one-third (i.e., from 3:0 to 3:1, wild:cultured fish). Thus, small-scale hatchery releases have the potential to make a substantial contribution to striped mullet production at this nursery site.

A key question remaining is what level of striped mullet abundances can the Kahaluu nursery support without adversely affecting wild stocks? How far below carrying capacity is this nursery now, and how near to that level should one attempt to get?

A large proportion of cultured fish in this study remained at the treatment site, yet they had a higher dispersal rate than did their wild counterparts at that site. The greater dispersal of hatchery fish suggests that cultured striped mullet might provide a useful tool for evaluating carrying capacity in these nursery habitats. One way to examine carrying capacity in Kaneohe Bay might be to use releases of cultured striped mullet to identify release magnitudes at which cultured fish show accelerated movement out of the habitat. In this study, about 12 to 15% appeared to be the dispersal rate for striped mullet in an unfamiliar nursery habitat.

The quantified results of hatchery contributions to wild stocks in Hawaii, Norway (Svasand et al. 1990), Japan (Honma 1993), California (Drawbridge et al., this volume), and Florida (Willis et al., this volume) indicate that marine enhancement has potential to increase abundances of targeted marine organisms. Given this potential, a responsible approach is needed to develop its use as an additional fishery management tool in coastal ecosystems (Blankenship and Leber, this volume). The results of this study document that small-scale releases of juveniles can increase striped mullet abundances in nursery habitats in Kaneohe Bay without displacing wild stocks. These results, combined with data showing that release season and release habitat appear to interact with fish SAR in controlling survival of cultured striped mullet in the wild (Leber, in press; Leber et al., in press; Leber, unpublished data), provide the minimum information needed to control hatchery-release effect on striped mullet population size.

To ensure that stocks are actually enhanced by hatchery-release activities, this sort of information from pilot studies needs to be coupled with additional management considerations to provide a controlled approach to marine enhancement—development of species management plans, well-defined indicators of success, prevention of genetic inbreeding and outbreeding depression, disease and health management, consideration of ecological interactions, identification of socioeconomic realities, and use of an adaptive management strategy (Blankenship and Leber, this volume).

In summary, there was no treatment effect in this experiment; hatchery releases did not displace wild individuals from the principal nursery habitat in Kaneohe Bay. The cultured fish released in this study increased abundances of striped mullet at the treatment site by around 33%. If these results were repeated in releases over several time periods, then even small-scale releases could help replenish the depleted striped mullet fishery in Kaneohe Bay. Conducting small-scale releases of cultured striped mullet in several nursery habitats in Kaneohe Bay should increase overall striped mullet abundances in this estuary.

This study corroborates earlier experiments that indicate hatchery releases can increase inshore fish abundances in Hawaii. If a careful approach is used, marine stock enhancement has considerable potential as an additional fishery management tool.

Acknowledgments

The authors wish to acknowledge several colleagues who participated in this study. We thank Lee Blankenship and Dan Thompson, of the Washington Department of Fish and Wildlife (WDFW), and Anthony Morano, Glenn Karimoto, Marcus Boland, Ryan Takushi, and all of the researchers in The Oceanic Institute Finfish Program for their tireless dedication in the tagging, field collection, laboratory work, and aquaculture work involved in this project. We thank Lee Blankenship, Rich Lincoln, Jim Shaklee, Ray Buckley, Dave Sterritt, and Jim West at WDFW for many fruitful discussions about the need to evaluate interactions of cultured fish with wild populations. We also thank Laurie Peterson for editing assistance and help with the graphics and Dave Sterritt for help with the database and graphics. This paper is funded by a grant from the National Oceanic and Atmospheric Administration (NOAA). The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its subagencies.

References

Bergman, P. K., F. Haw, H. L. Blankenship, and R. M. Buckley. 1992. Perspectives on design, use, and misuse of fish tags. Fisheries (Bethesda) 17(4):20–24.

Blankenship, H. L., and K. M. Leber. 1995. A responsible approach to marine stock enhancement. American Fisheries Society Symposium 15:167–175.

Buckley, R. M., and H. L. Blankenship. 1990. Internal extrinsic identification systems: overview of implanted wire tags, otolith marks and parasites. American Fisheries Society Symposium 7:173–182.

Bryan, D. F., D. A. Rutherford, and B. Walker-Bryan. 1992. Acidification of the lower Mississippi River. Transactions of the American Fisheries Society 121(3):369–377.

Coutin, P. C., and I. A. Payne. 1989. The effects of long-term exploitation of demersal fish populations off the coast of Sierra Leone, West Africa. Journal of Fish Biology 35:163–167.

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. American Fisheries Society Symposium 15:568–569.

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

Fox, W. 1992. Testimony at Congressman G. Studds' Congressional Committee Hearing. U.S. Congressional Record HMM2750221992, Washington, DC.

Hardin, G. 1968. The tragedy of the commons. Science 162:1243–1248.

Honma, A. 1993. Aquaculture in Japan. Japan FAO Association, Chiyoda-Ku, Tokyo.

Kent, D. B., M. A. Drawbridge, and R. F. Ford. 1995. Accomplishments and roadblocks of a marine stock enhancement program for white seabass in California. American Fisheries Society Symposium 15:492–498.

Leber, K. M. In press. Significance of fish size-at-release on enhancement of striped mullet fisheries in Hawaii. Journal of the World Aquaculture Society.

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* Proceedings of the First Biennial Symposium for the Main Hawaiian Islands Marine Resources Investigation. Hawaii Department of Land and Natural Resources, Division of Aquatic Resources, Technical Report 94-03, Honolulu.

Moyle, P. B., B. Herbold, D. E. Stevens, and L. W. Miller. 1992. Life history and status of Delta Smelt in the Sacramento–San Joaquin Estuary, California. Transactions of the American Fisheries Society 121(1):67–77.

NOAA (National Oceanic and Atmospheric Administration). 1991. Our living oceans: first annual report on the status of U.S. living marine resources. NOAA Technical Memorandum NMFS (National Marine Fisheries Service) F/SPO-1.

NOAA (National Oceanic and Atmospheric Administration). 1992. Our living oceans: report on the status of U.S. living marine resources 1992. NOAA Technical Memorandum NMFS (National Marine Fisheries Service) F/SPO-2.

Oceanic Institute. 1991. Stock enhancement of marine fish in the state of Hawaii (SEMFISH) phase 4. Annual Report to National Marine Fisheries Service, Honolulu.

Ross, M. R., and G. A. Nelson. 1992. Influences of stock abundance and bottom-water temperature on growth dynamics of haddock and yellowtail flounder on Georges Bank. Transactions of the American Fisheries Society 121(5):578–587.

Stroud, R. H., editor. 1986. Fish culture in fisheries management. American Fisheries Society, Fish Culture Section and Fisheries Management Section, Bethesda, Maryland.

Svasand, T., K. E. Jorstad, 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. Journal du Conseil International pour l'Exploration de la Mer 47:5–12.

Svasand, T., and T. S. Kristiansen. 1990. Enhancement studies of coastal cod in western Norway, part 4. Mortality of reared cod after release. Journal du Conseil International pour l'Exploration de la Mer 47:30–39.

Tsukamoto, K., and six coauthors. 1989. Size-dependent mortality of red sea bream, *Pagrus major*, juveniles released with fluorescent otolith-tags in News Bay, Japan. Journal of Fish Biology 35(Supplement A):59–69.

Wilkinson, L. 1990. SYSTAT: the system for statistics. Systat, Evanston, Illinois.

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. American Fisheries Society Symposium 15:354–365.