

## Significance of Fish Size-At-Release on Enhancement of Striped Mullet Fisheries in Hawaii

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### Abstract

A tag-release-recapture study was conducted to evaluate size-at-release impacts upon recruitment of cultured, juvenile striped mullet, *Mugil cephalus* released in inshore habitats of Oahu, Hawaii, USA. In June and July 1990, 85,848 juvenile mullet were graded into five size groups (ranging from 45 to 120 mm in length), identified with binary-coded wire tags, and released into two estuaries ( $2 \times 5$  factorial design). Of the tagged fish, 42,822 were released into Kaneohe Bay on the east (windward) coast of Oahu; 43,026 were released into Maunalua Bay on Oahu's dryer south shore. The fish were released into both bays simultaneously. Releases were blocked in time across 5 release lots. To evaluate growth and survival rates of released mullet, both bay systems were sampled monthly with cast nets over a ten-month period after release. Overall, 733 tagged *M. cephalus* were recaptured, 277 from Kaneohe Bay and 456 from Maunalua Bay. Overall proportions of tagged fish in samples declined from 33.4% ( $\pm 25.2\%$ ) of the total *M. cephalus* catch at week 5 to 1.88% ( $\pm 0.95\%$ ) by week 23. From week 23 on, tagged fish averaged 2.09% ( $\pm 0.23\%$ ) of the striped mullet in monthly samples. Within 9 wk after releases, recapture frequencies were clearly skewed in favor of fish that were larger at the time of release. Fish smaller than 70 mm when released were rare or absent in collections within 18 wk after release. This confirms results of a smaller-scale pilot study in Maunalua Bay and shows that fish size-at-release can have a major impact on the success of hatchery releases in marine habitats. Pilot studies to identify minimum fish size-at-release should be conducted at all sites targeted for full-scale marine hatchery releases.

The potential of hatchery releases to help replenish depleted marine fish stocks is being evaluated in Hawaii, where inshore and nearshore fish populations appear to have suffered major declines in abundance during this century. A series of pilot hatchery releases of native striped mullet *Mugil cephalus* are being conducted to examine the impacts of release protocols on growth and survival of cultured and released fingerlings (The Oceanic Institute 1990, 1991). These pilot experiments are identifying release parameters for a larger-scale test of the marine stock-enhancement concept in Hawaii.

Although full-scale hatchery releases are conducted in open marine habitats (e.g., Rutledge and Matlock 1986; Honma 1993), little direct information exists for evaluating the impacts of releases in marine systems on fish population size and on fishery yields. To design an effective test of the marine hatchery release concept, there are several key issues regarding release strategy that

need to be resolved. The importance of conserving genetic diversity among released fingerlings is a primary concern (Shaklee et al. 1993a, 1993b; Blankenship and Leber 1995). This study addresses a key question about the logistical success of releases: to what extent is post-release survival directly impacted by fish size at the time of release?

A pilot tag-release-recapture study in Maunalua Bay, on Oahu, Hawaii, revealed that cultured *M. cephalus* could survive and grow in a back-reef marine environment, but that fish size-at-release appeared to have a major impact upon recapture rates (and presumably survival) of tagged, juvenile striped mullet in their nursery habitats (The Oceanic Institute 1990). The smallest fish released were underrepresented in field collections made in Maunalua Bay; individuals less than 70 mm total length (TL) when released dropped completely out of field samples within 11 wk after release (The Oceanic Institute 1990).

Because of the importance of a minimum size requirement for survival of hatchery-released fish, corroboration is needed of the size-at-release impact observed in the initial Maunalua Bay study. This study examines if the impact of fish size-at-release on recapture rate is reproducible in Maunalua Bay, and whether size-at-release based differential mortality also occurs in more favorable striped-mullet nursery habitats located in Kaneohe Bay, Hawaii. A rigorous test of fish size-at-release impact was performed: 1) by releasing over five times the number of fish released in the initial study; 2) by releasing relatively high proportions of fish smaller than 70 mm TL (the critical size for survival in the initial study); and 3) by replicating the study in another mullet nursery habitat, Kaneohe Bay.

This study is part of a research program established to develop and test hatchery release strategies for replenishing depleted marine fisheries in Hawaiian coastal waters. The research program, titled "Stock Enhancement of Marine Fish in the State of Hawaii (SEMFISH)," is funded by the United States National Marine Fisheries Service.

### Materials and Methods

Striped mullet *Mugil cephalus* were spawned at The Oceanic Institute, Oahu, Hawaii, and reared to fingerlings during winter and spring 1990. Batches of mullet eggs were hatched approximately every 6 wk over a 5-mo period. Larvae from each batch were cultured in 5,000-L tanks for approximately 40 d, and nursed for 2–6 mo in ponds and tanks at The Oceanic Institute and in ponds at the University of Hawaii Mariculture Research and Training Center in Kahaluu, Hawaii.

During the period 15 May through 19 July 1990, juvenile *M. cephalus*, ranging in size from 40 to 130 mm TL were harvested from nursery ponds and transported to 40,000-L holding tanks at the Institute. Fish were graded into five size groups; 90,406 were marked with internal binary coded wire tags

(Northwest Marine Technology, Inc., Olympia, Washington). Tags were implanted in the snout area using an automatic injector with head molds fabricated specifically for striped mullet by Washington Department of Fish and Wildlife biologists. Evaluation of target tissue and verification of the tag system for this species are dealt with elsewhere (Northwest Marine Technology, Inc. 1989; The Oceanic Institute 1990). All individuals released were tagged.

The tags identified fish size-at-release, release site and release date (lot). Batch codes were used to identify five size groups—45–60 mm TL; 60–70 mm; 70–85 mm; 85–110 mm; and 110–130 mm, and two bay systems—Maunalua Bay on Oahu's south shore, and Kaneohe Bay on Oahu's windward (eastern) coast. There was size variation in all batches of mullet reared for this study. However, the primary difference among fish size-at-release groupings was fish age.

Pilot studies have documented for *M. cephalus* a 97% tag-retention rate 12 mo after tagging (The Oceanic Institute 1990). To verify that tag-retention rates were that high in this study, at least 5% of the tagged fish from each release lot were randomly subsampled prior to each release. These subsamples, totaling 4,558 fish, were retained in tanks for up to 6 mo and periodically checked for tag retention. The subsampled fish were not released.

Tagged *M. cephalus* were released in five lots over a 2-mo period. In each release lot, all size groups were released into each bay system nearly simultaneously (however, fish above 110 mm TL were unavailable after lot 2). In the first lot, fish were released into Kaneohe Bay in the morning and into Maunalua Bay that afternoon (Fig. 1). Morning and afternoon releases were alternated during successive release lots.

Tagged *M. cephalus* were released into Maunalua Bay at Kawaikui Beach Park, a south-facing beach near the middle of the bay and the site of the previous releases. Salinities at Kawaikui were typically 25–35

ppt. In Kaneohe Bay, two of the five lots of fish released were stocked at Kahaluu Stream mouth in the north part of the bay. This is an east-facing shore. Salinities at the Kahaluu site ranged from 5–8 ppt during releases. This site is adjacent to Kahaluu lagoon, which is a principal nursery habitat for *M. cephalus* juveniles.

Because of a perceived increase in commercial bait fish collection activities near Kahaluu Stream after the first two experimental lots were released, the last three lots introduced into Kaneohe Bay were released from the Hawaii Institute of Marine Biology pier in the southern part of the bay. Salinities at pier ranged from 28 to 35 ppt during releases. All releases were made near the shoreline in water 0.5–1.5 m deep.

Beginning in June 1990 released and wild *Mugil cephalus* abundances were monitored monthly for 10 mo by sampling with cast nets. Recaptured tagged fish were removed from collections and returned to the laboratory for tag analysis. The first field collection began 4 wk after lot 1 was planted (1wk after lot 2). All release lots were in place prior to the second field collection.

Each field collection was conducted over approximately a 2-wk period. The monthly sampling design entailed collections at four stations within each bay system. Collections were made during the day over approximately an 8-h period at each station. Stations were established at *M. cephalus* nursery habitats, various tributaries located throughout each bay (The Oceanic Institute 1990). At each station, two substations were sampled, one established upstream, the other in the bay near the mouth of the tributary. Within substations, 15 cast net throws were made. To broaden the range of microhabitats and fish size-ranges sampled, two sizes of cast nets were employed. Ten of the 15 casts per substation were made with a 16-ft (4.9-m) diameter,  $\frac{3}{8}$ -in (9.5-mm) mesh net, and five casts were made with a 10-ft (3-m) diameter,  $\frac{1}{4}$ -in (6-mm) mesh net. Thus, 120 casts were made in each bay system during each sample month.

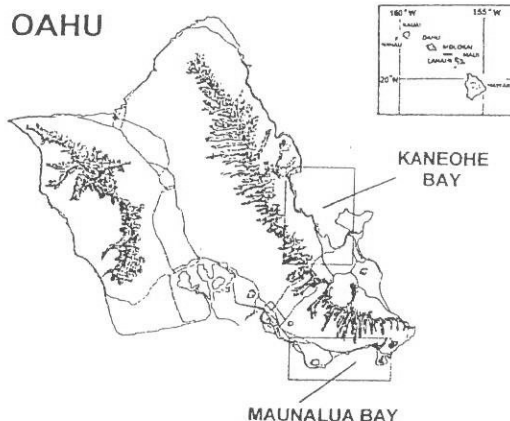


FIGURE 1. Map of Oahu illustrating location of study sites.

Placement of net samples was not random at sampling stations, but stratified over schools of mullet juveniles. Random sampling yielded few wild mullet, and very few tagged individuals. Mullet schooled in fairly low densities within these clear-water habitats, and our collections targeted these schools. Nevertheless, the data used to determine proportions of tagged versus untagged mullet were randomly distributed, because we had no indication that schools, once sighted, contained tagged individuals.

All mullet collected were measured and checked for tag presence using a portable tag detector (Northwest Marine Technology, Inc., Olympia, Washington). Tagged mullet were placed on ice and returned to the laboratory where they were thawed, weighed, and measured.

Treatment identifications were based on the tags retrieved from recaptured fish. Tags were extracted using a binary search to locate them within the snout region. Tags were decoded using a binocular microscope (40 $\times$ ). Around 4% of the tags from recaptured fish were lost during extraction. This error rate has declined to <1% in follow-up studies. Tags were first decoded at the Institute by SEMFISH biologists; following the initial decoding, the tags and code data were sent to Lee Blankenship at the Washington Department of Fish and Wildlife

TABLE 1. Release statistics from the summer 1990 releases of cultured *Mugil cephalus* into Kaneohe Bay and Maunalua Bay on Oahu, Hawaii.

Release date	Release size (mm TL)					Total released
	45-60	60-70	70-85	85-110	110-130	
Release site: Kaneohe Bay						
6/1/90	135	1,171	3,076	811	60	5,253
6/20/90	267	1,824	2,824	1,066	442	6,423
7/14/90	616	2,902	6,717	258	0	10,493
7/21/90	4,479	3,265	4,331	206	0	12,281
7/28/90	2,128	1,645	4,232	367	0	8,372
Subtotal	7,625	10,807	21,180	2,708	502	42,822
Release site: Maunalua Bay						
6/1/90	135	1,244	3,082	815	60	5,336
6/20/90	262	1,777	2,873	1,070	446	6,428
7/14/90	636	2,998	6,703	258	0	10,595
7/21/90	4,509	3,280	4,311	207	0	12,307
7/28/90	2,122	1,632	4,238	368	0	8,360
Subtotal	7,664	10,931	21,207	2,718	506	43,026
Grand total	15,289	21,738	42,387	5,426	1,008	85,848

where the tags were read again to confirm the code data.

Data were analyzed using Systat (Wilkinson 1990). Systat Basic was used to write tag-decoding algorithms. The algorithms identified release date, release site, and fish size-at-release for each recaptured fish, based on the binary tag codes. An error-check algorithm was also written. Variance estimates are expressed throughout as standard errors.

## Results

### Release Statistics

During June and July 1990, 85,848 juvenile striped mullet were released on Oahu into Kaneohe and Maunalua Bays. Numbers of tagged and released fish varied among size groups and among release lots, but were held nearly constant between bay systems (Table 1).

Subsamples of all sizes of tagged fish from each release lot, totaling 4,558 individuals, were held at the Institute for up to 6 mo after tagging. Tag retention in those subsamples averaged 98.6% ( $\pm 0.4\%$ ) (Table 2).

After five weeks in the wild, the size structure of tagged *Mugil cephalus* established by

these releases led that of the 1990 recruitment pulse of wild mullet in both bay systems by a small margin. On week 5 in Maunalua Bay (Fig. 2), median size of recaptured hatchery-released *Mugil cephalus* was 89 mm TL ( $N = 210$ ), 17 mm greater than the median size ( $N = 75$ ) of wild young-of-the-year (individuals  $< 120$  mm TL) in Maunalua Bay. In Kaneohe Bay, median size of released mullet was 82 mm TL ( $N = 38$ ), 11 mm larger than wild young-of-the-year ( $N = 414$ , Fig. 3). Note that median size of the earlier recruitment pulse of wild mullet in both bays, which represents summer recruitment in 1989, is double the median size of 1990 recruits (median = 145 mm [ $N = 75$ ] and 168 mm TL [ $N = 9$ ] in Maunalua and Kaneohe Bay, respectively).

### Impact of Release System

We recaptured 733 cultured striped mullet during the 10-mo period following summer 1990 releases; 277 of these were collected in Kaneohe Bay, where cultured fish comprised 4.6% of the mullet collected; 456 were collected in Maunalua Bay and comprised 15.5% of the mullet collected there. The disparity between bays in total numbers of recaptured cultured fish was largely

TABLE 2. Coded-wire tag retention in random subsamples of *Mugil cephalus* collected from each release lot and held for 1 to 6 mo after tagging. N = number of individuals randomly subsampled from each release group.

Re-lease lot	Kaneohe Bay (N)	Maunalua Bay (N)	Holding period	Percent retention
1	285	286	2 mo	97.3%
2	337	337	4 mo	98.3%
3	573	566	6 mo	99.4%
4	647	647	6 mo	99.6%
5	440	440	1 mo	98.4%
Total	2,282	2,276		98.6% ( $\pm 0.4\%$ )

due to a sampling artifact during the first two recaptures. On the third recapture in Kaneohe Bay, we located tagged fish at a location farther upstream than had been previously sampled. Sampling at that same upstream location 7 days after a follow-up release in 1991 produced large numbers of tagged individuals.

Cultured, tagged and released mullet averaged 8.28% ( $\pm 3.55\%$ ) of the total mullet

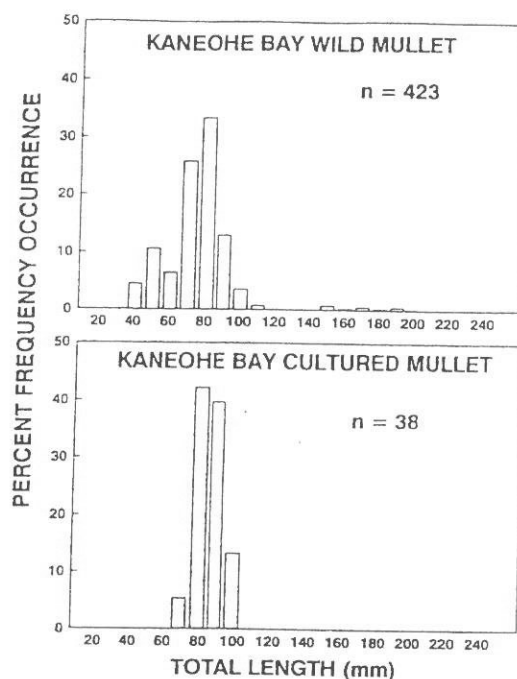


FIGURE 3. Size structures of wild and cultured striped mullet in collections taken from Kaneohe Bay 5 wk after the first release in 1990.

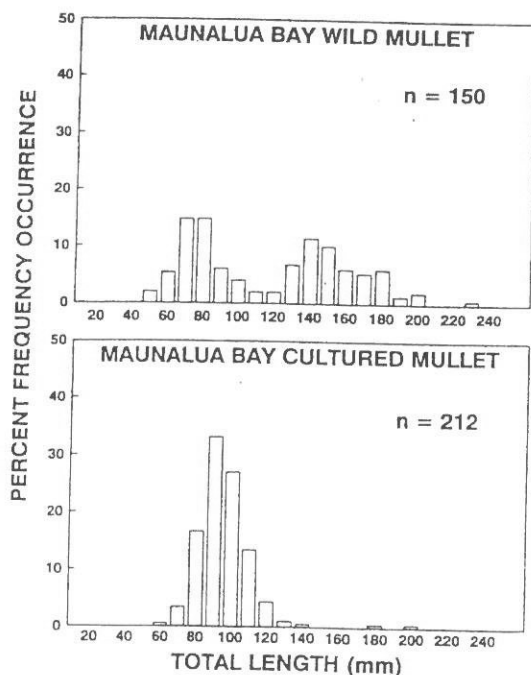


FIGURE 2. Size structures of wild and cultured striped mullet in collections taken from Maunalua Bay 5 wk after the first release in 1990.

catch in our samples (Table 3). The contribution of cultured and released mullet to samples of wild mullet ranged from 58% in Maunalua Bay 5 wk after release to around 2% in both bay systems after 10 mo in the wild. Overall proportions of tagged fish in samples declined in both bays through week 23 (Fig. 4). From week 23 through week 46, tagged fish averaged 2.09% ( $\pm 0.23$ ) of the total striped mullet in our monthly samples. Contribution rates were not significantly different between bays.

Following the second recapture effort (from week 18 on), nearly twice as many cultured *M. cephalus* were retrieved from cast net samples in Kaneohe Bay compared to those in Maunalua Bay (Fig. 4). From week 23 on, abundance of cultured fish in Kaneohe Bay collections (standardized to number per 15 cast-net samples in Table 3) averaged 1.53 ( $\pm 0.42$ ), nearly double the 0.78 ( $\pm 0.21$ ) individuals per 15 samples in Maunalua Bay. This difference was marginally significant ( $T = 2.53$ ,  $df = 5$ ,  $P = 0.05$ ).

TABLE 3. Abundances of hatchery-released and wild *Mugil cephalus* in collections from Kaneohe Bay (KBAY) and Maunalua Bay (MBAY). Data are standardized to numbers per 15 cast net throws.

Weeks after release	Hatchery-released tagged mullet				Wild (untagged) striped mullet				Percent contribution of tagged fish			
	KBAY	MBAY	Mean	(SEM)	KBAY	MBAY	Mean	(SEM)	KBAY	MBAY	Mean	(SEM)
5	7.6	26.5	17.1	(9.5)	84.6	18.8	51.7	(32.9)	8.2	58.6	33.4	(25.2)
9	19.5	19.0	19.3	(0.3)	126.7	33.2	79.9	(46.7)	13.3	36.4	24.9	(11.5)
18	6.0	2.3	4.1	(1.9)	142.6	62.6	102.6	(40.0)	4.0	3.5	3.8	(0.3)
23	2.3	0.5	1.4	(0.9)	77.3	53.5	65.4	(11.9)	2.8	0.9	1.9	(1.0)
28	1.6	1.3	1.5	(0.2)	66.1	68.4	67.3	(1.2)	2.4	1.8	2.1	(0.3)
34	3.1	1.5	2.3	(0.8)	85.1	40.6	62.9	(22.3)	3.5	3.6	3.6	(0.0)
38	1.0	0.8	0.9	(0.1)	54.3	36.5	45.4	(8.9)	1.8	2.0	1.9	(0.1)
42	0.4	0.3	0.3	(0.1)	58.6	29.4	44.0	(14.6)	0.7	0.8	0.8	(0.1)
46	0.8	0.4	0.6	(0.2)	28.0	18.6	23.3	(4.7)	2.6	2.0	2.3	(0.3)
Mean (SEM)	4.7 (2.0)	5.8 (3.3)	5.3 (1.9)		80.4 (11.9)	40.1 (6.0)	60.3 (8.1)		4.4 (1.3)	12.2 (6.9)	8.3 (3.5)	

Abundances of wild *M. cephalus* were also significantly greater in Kaneohe Bay collections ( $T = 3.64$ ,  $df = 8$ ,  $P < 0.007$ ). Standardized mean number of wild individuals in Kaneohe Bay samples was  $80.36 (\pm 11.9)$ . As with hatchery-released *M. cephalus*, this figure is also double the mean from Maunalua Bay ( $40.2 [\pm 6.0]$ ). Proportions of cultured fish in samples were nearly equal in both bay systems.

#### Impact of Fish Size-at-Release

Within 6 wk after release, recapture frequencies were significantly skewed in favor of fish that were larger at the time of release

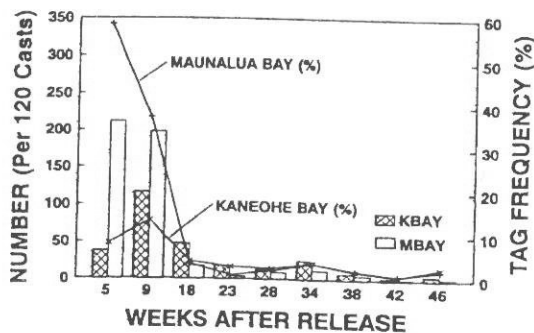


FIGURE 4. Total number of tagged *Mugil cephalus* (bars) and tag frequency (lines) in collections made over a 46-wk period following 1990 releases in Kaneohe Bay (KBAY) and Maunalua Bay (MBAY). Tag frequency is number of tagged *M. cephalus* recaptured/total *M. cephalus* in samples  $\times 100\%$ .

in both bay systems studied (Figs. 5, 6). Individuals smaller than 70 mm TL when they were released were either rare or completely absent in collections within 18 wk after the first release into Maunalua Bay and within 28 wk in Kaneohe Bay. After these time periods, the smaller the fish at the time of release, the lower the recapture frequency in both bay systems.

A statistically significant relationship between fish size-at-release and recapture rates was apparent in both bay systems (ANOVA,  $P < 0.01$ ). Fish less than 60 mm when released were rare in all samples except in week 9 collections from Maunalua Bay. Although release lots 4 and 5 were heavily weighted towards individuals less than 70 mm (63% and 45% of the fish released in lots 4 and 5, respectively, Table 1), few were recaptured. Following week 9, recaptures from the last two release lots were negligible (five *M. cephalus* from lots 4 and 5 taken in collections after week 9 were all greater than 70 mm when released).

#### Growth of Hatchery-Released *Mugil Cephalus*

When data from both bay systems were pooled, mean lengths of hatchery-released and wild fish were similar, except during week 42 (Table 4). Hatchery-released fish clearly grew over the course of this study.

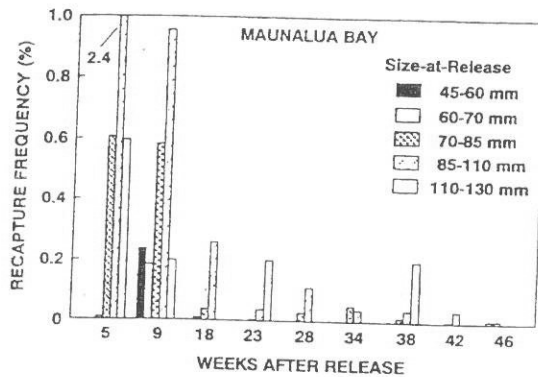


FIGURE 5. Size-at-release based recapture rates for cultured *Mugil cephalus* taken in Maunalua Bay collections. Recapture frequencies were computed within fish size-at-release treatment groups and are number recaptured/number released within treatment group  $\times 100\%$ .

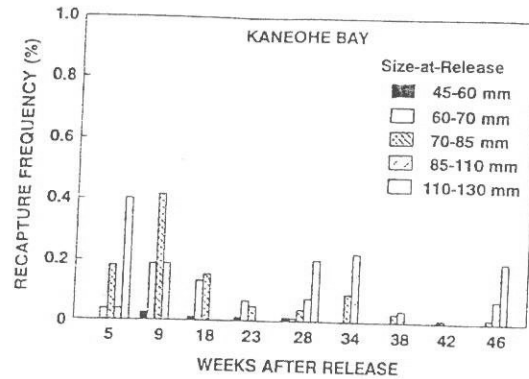


FIGURE 6. Size-at-release based recapture rates for cultured *Mugil cephalus* taken in Kaneohe Bay collections. Recapture frequencies were computed within fish size-at-release treatment groups and are number recaptured/number released within treatment group  $\times 100\%$ .

Because of the small sample size of tagged fish in samples from Maunalua Bay after week 18, comparison of fish lengths between bay systems is not warranted.

#### Discussion

Striped mullet are catadromous fish that prefer low-salinity habitats during early juvenile stages. Kaneohe Bay was viewed here as a better striped mullet nursery habitat than Maunalua Bay because runoff and stream flow rates are considerably greater in Kaneohe Bay (Devaney et al. 1982). Given the relatively low stream flow rates in Maunalua Bay, that system appears to be a

poorer juvenile recruitment habitat than some of the other Oahu estuaries with greater average annual rainfall values.

Cultured striped mullet clearly survived and grew in the wild in this study. Although we observed differences between bays in numbers of tagged fish collected, within 18 wk after initial releases there were strong similarities in contribution rates and in size-at-release impacts in Maunalua Bay and Kaneohe Bay. In both bay systems, the impact of hatchery-released mullet on abundances of striped mullet in the wild stabilized at around 2% within 23 wk after release.

TABLE 4. Mean length of hatchery-released and wild *Mugil cephalus* in collections from Kaneohe Bay (KBAY) and Maunalua Bay (MBAY) following 1990 releases.

Weeks	Hatchery-released tagged mullet				Wild (untagged) striped mullet			
	KBAY	MBAY	Mean	(SEM)	KBAY	MBAY	Mean	(SEM)
5	81.6	94.5	88.0	(6.5)	68.5	108.6	88.6	(20.1)
9	86.9	79.4	83.1	(3.8)	78.8	97.3	88.1	(9.3)
18	78.3	97.4	87.8	(9.6)	101.0	88.1	94.6	(6.5)
23	90.3	147.8	119.0	(28.7)	121.5	105.6	113.6	(8.0)
28	118.3	101.5	109.9	(8.4)	132.8	93.3	113.1	(19.8)
34	122.1	106.2	114.1	(7.9)	119.1	96.1	107.6	(11.5)
38	136.7	157.7	147.2	(10.5)	153.4	110.4	131.9	(21.5)
42	126.7	175.5	151.1	(24.4)	114.3	102.0	108.2	(6.2)
46	160.8	118.8	139.8	(21.0)	150.5	112.0	131.3	(19.3)
Mean	111.3	119.8	115.6	(7.1)	115.5	101.5	108.5	(5.2)
(SEM)	(9.5)	(10.9)			(9.7)	(2.8)		

The clear impact of fish size-at-release on recapture rates observed here confirms results from a smaller study conducted over a 6-mo period in Maunalua Bay (The Oceanic Institute 1990). In that study, in which over 15,000 tagged juveniles were released in November 1989, no cultured mullet smaller than 70 mm at release were recaptured after 11 wk in the wild. In comparison, hatchery releases were conducted in the summer in this study. Despite the difference in release season in these two studies, the size of hatchery-reared mullet at the time of release appears to have had a critical impact on survival. Gear bias was not a factor here. Small (50 to 70-mm long) wild mullet were abundant in our cast-net samples throughout the study (The Oceanic Institute 1991).

At least two hypotheses could explain the observed size-at-release impact on recapture rates in these open bay systems. Greater success over time in recapturing the larger individuals released could be explained by size-dependent differential survival, or by differential dispersal patterns, or both. Both of these mechanisms could be closely tied to habitat quality.

Whereas differential dispersal rates would dilute stocking impact upon localized stocks in the vicinity of the release habitat, but not necessarily in adjacent habitats, differential survival would reduce or eliminate juveniles smaller than a critical size. Differential survival is thus the more important of these two alternative explanations for size-at-release impact, as failure to recognize it could lead to mortality of the majority of released individuals.

It is unlikely that the paucity of smaller cultured mullet in our field samples was caused by emigration of the smaller individuals released out of our study areas. Most of the recaptured cultured mullet that were released near Kahaluu Lagoon in Kaneohe Bay were recovered less than 1 km away from the release site, indicating little dispersal from that nursery area (The Oceanic Institute 1991). Yet none of the smaller in-

dividuals tagged were recaptured there following 28 wk after their release. Also, our sampling stations were clearly established in representative *M. cephalus* habitats, and small wild mullet were usually abundant in those collections (The Oceanic Institute 1991).

Was the observed size-at-release impact upon recapture rates caused by differential predation? Several studies have documented the role that habitat complexity can play in mediating predation (e.g., Stoner 1982; Leber 1985). In areas where nursery habitats have been degraded, predation could have a disproportionate impact on survival of smaller mullet, particularly if the degradation resulted in reduced access for juveniles to low salinity habitats.

Major (1978) has shown that 40-mm juvenile mullet recruit into very shallow water, only a few centimeters deep in Maunalua Bay, which provides refuge from predators. Blaber (1987) suggests that turbidity associated with fresh water inputs is the most important cue mediating juvenile *Mugil cephalus* migrations into estuaries and streams in South Africa. The cues for continued movement upstream are obscure, but they may relate to salinity preferences (Cyrus 1985). During this study, wild mullet fingerlings moved farther upstream (and into lower salinities) than larger mullet (personal observation), a behavior that would allow small individuals to avoid many of the marine predators found in higher salinities in Kaneohe and Maunalua Bay.

Because of reduced fresh water inputs associated with land development near Maunalua Bay, smaller mullet were often displaced from their recruitment habitats in Maunalua Bay. During our field sampling, we frequently observed many of the tributaries historically frequented by striped mullet to be dry or with much reduced flow rates. At two of our principal sampling stations in Maunalua Bay, highway construction in 1991 had completely prevented dispersal of juvenile fishes into upstream habitats.

During the past 75 yr, Kaneohe Bay has experienced a large reduction in fresh water inputs, as its principal tributaries have been channelized to shunt stream flow through the Koolau Mountain range to the interior of Oahu for irrigation and domestic use. Devaney et al. (1982) estimated that these water diversion projects represent a decrease of over 40% in total stream runoff into the Bay. The reduction of fresh water runoff into these bays has clearly impacted salinity regimes in the principal tributaries, and has altered the primary refugia for *M. cephalus* recruits.

Interactions between size-at-release impact and both release habitat and release season need to be understood. Experiments comparing responses of hatchery-releases in different nursery habitats and during different release seasons are needed to plan release strategies in full-scale enhancement programs. Subsequent releases in Kaneohe Bay following this study showed that both wild and cultured mullet had strong habitat affinity and tended to remain within or near the streams where they were released (Leber et al. 1995). That study lends further support to our premise that differential survival was a primary factor controlling size-at-release in this study.

In habitats where survival rate is directly proportional to size-at-release, identifying a lower limit for the length of fish to be released should be a primary concern for stock enhancement programs. Other studies have shown size-at-release impacts on recapture rates following releases of cultured aquatic organisms (Hager and Noble 1976; Bilton et al. 1982; Tsukamoto et al. 1989; Svasand and Kristiansen 1990; Ray et al. 1994). Because of the clear potential to affect success of hatchery releases, size-at-release impact should be one of the first factors investigated before conducting full-scale stock enhancement programs.

If predation is an important regulator of fish size-at-release impact, then releases timed to avoid seasons when predators of small mullet are abundant should increase

survival and recapture rates of *Mugil cephalus* <70 mm in length. If access of released juveniles to optimum nursery habitats mediates size-at-release based differential predation, then releases into low salinity micro-habitats should increase survival and recapture rates of *M. cephalus* <70 mm in length at release. Disproportionally greater recapture of individuals that were small (<70 mm long), over those that were large at the time of release, from areas outside of the principal release habitat would support the differential dispersal hypothesis.

Based on the present study, the "critical release size" for enhancing local *Mugil cephalus* populations through summer releases, either in Maunalua Bay or in Kaneohe Bay, appears to be 70 mm TL. The probability of individuals <70 mm at the time of release surviving in these systems appears to be extremely poor.

"Critical release size" is defined here as the size-at-release below which the probability of survival to reproductive size approaches zero. In comparison, "optimum release size" is defined as the size at which maximum returns in a stock enhancement program would be achieved. "Critical release size" is a function of survival in the wild. "Optimum release size" for fishery enhancement is a function of survival, growth rates, hatchery and release costs, and the socio-economic value of increased harvest levels, and/or stock abundances, gained from releasing larger fish. For a sport fishery, value can be derived using contingency valuation methods, such as willingness to pay surveys (e.g., Brookshire et al. 1980). Where replenishment is valued based not on fishery landings, but on increased abundance of wild populations, some measure of ecological value would also be needed. In order to evaluate the feasibility of marine stock enhancement programs, critical release size and optimum release size need to be clearly defined for all environments and seasons targeted for hatchery releases.

If size-at-release impact on recapture rate is not a global phenomenon, but is depen-

dent upon such factors as release season and release habitat, then rearing costs in a hatchery-release program would vary with the timing and location of releases. Given the direct relationship that exists between culture costs and length of the growout period required to attain release size, any reduction in critical release size, and the associated reduction in optimum release size that this might allow, could significantly reduce costs to supplement or replenish marine fish populations.

### Acknowledgments

The field work in this study was conducted by Steve Arce and Nathan Brennan. Lee Blankenship, Dan Thompson and Raymond Buckley of the State of Washington Department of Fish and Wildlife provided invaluable assistance in applying coded wire tagging methods to striped mullet. Bong Kim and The Oceanic Institute's Finfish Program provided the expertise and assistance needed to produce the fish released here. Dave Sterritt helped with the graphics and data reduction. This project was funded by a grant from the National Oceanic and Atmospheric Administration. The views expressed herein are those of the author and do not necessarily reflect the views of NOAA or any of its sub-agencies.

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