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RECRUITMENT PATTERNS OF CULTURED JUVENILE PACIFIC THREADFIN, *POLYDACTYLUS SEXFILIS* (POLYNEMIDAE), RELEASED ALONG SANDY MARINE SHORES IN HAWAII

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ABSTRACT

Release-recapture studies were conducted with Pacific threadfin, *Polydactylus sexfilis*, the species given highest priority for stock-enhancement research in Hawaii. Their purpose was to evaluate recruitment potential, dispersal, growth, and differential recapture rates of cultured fingerlings released into shoreline juvenile nursery habitats along the windward (eastern) coast of Oahu, Hawaii. We varied fish size at release, release site, and the seasonal timing of releases using a balanced, randomized-block experimental design. After releases of 20,000 tagged Pacific threadfin in 1993 and about 81,000 in 1994, we recaptured 1705 cultured juveniles in net collections made over a 17-mo period. Presence of cultured fish in net samples depended strongly on the interactive effects of release variables. Size at release had an important effect on recapture rates at all release sites, but this effect varied seasonally. At one of the release sites, larger fish apparently had better survival after winter releases and smaller fish had better survival after summer and fall releases. Release site affected dispersal patterns, recruitment, and recapture rates. The percentage of cultured fish in samples of Pacific threadfin taken 8 mo after release varied from 0% to 64%. Cultured fish showed strong site fidelity at some sites, weak at others. What we considered "pilot"-scale releases clearly were large enough to approach swamping wild recruitment at Kahana Bay. A key question from this study is how many cultured juvenile Pacific threadfin the Kahana Bay site can support without displacement of wild individuals.

Worldwide declines in coastal fishery landings (FAO, 1994) have prompted a resurgence of interest in evaluating the potential of hatchery-based marine stock enhancement (release of cultured juveniles to increase abundance of wild stocks that spawn in seawater) as a tool to help replenish depleted fisheries (see symposium proceedings edited by Lockwood, 1991; Danielssen et al., 1994; and Schramm and Piper, 1995). Recent studies indicate that released cultured organisms can make substantial contributions to fishery landings of some coastal stocks (e.g., Kitada et al., 1992; Honma, 1993; Leber and Arce, 1996). Because of increased marine stocking, more information is needed for evaluation of the desirability and effectiveness of such releases (Peterman, 1991; Cowx, 1994; Blankenship and Leber, 1995; Munro and Bell, 1997).

Release-recapture studies in Hawaii are evaluating hatchery-release effects on marine and estuarine species with different trophic and habitat preferences. In 1988, Pacific threadfin, *Polydactylus sexfilis* (Polynemidae), was given the highest research priority in Hawaii among species evaluated for studies to examine the potential of marine stock enhancement as an additional fishery-management tool (Leber, 1994). The species is a marine carnivore. Juveniles prefer inshore, sandy marine habitats. Adults feed in sandy patches among reefs and in the surf zone along Hawaii's sandy and rocky shores. Pacific threadfin is a very popular sport fish that also supports a small subsistence fishery in Hawaii. Historically, this species was prized by the kings of Hawaii, who built saltwater fish ponds to grow wild juveniles for food. During this century, Pacific threadfin have declined

Table 1. Summary statistics for 20,010 fish tagged and released in 1993 for evaluation of hatchery releases in Kahana Bay and at Laie Beach. Unique batch codes were used to identify fish from each cell in the matrix. Lot 1 was released on 2 November, lot 2 on 16 November, and lot 3 on 7 December. All released fish were marked with coded-wire tags placed in the snout and visible implant elastomers within the adipose eyelid tissue.

		Release lots			
Release site	Size at release	1	2	3	Total
Kahana Bay	70–100 mm	970	1,562	1,737	4,269
	100–130 mm	1,400	1,758	1,416	4,574
	130–150 mm	258	489	430	1,177
	Subtotal	2,628	3,809	3,583	10,020
Laie Beach	70–100 mm	935	1,602	1,764	4,301
	100–130 mm	1,307	1,740	1,446	4,493
	130–150 mm	375	411	410	1,196
	Subtotal	2,617	3,753	3,620	9,990
Grand total		5,245	7,562	7,203	20,010

severely in abundance in Hawaii, especially on the island of Oahu, where many inshore fish populations have been depleted (Shomura, 1987).

The first step required in evaluating stock-enhancement potential of the Pacific threadfin was to develop aquaculture production technology, and progress has now been made in that area (Kelley et al., 1995; Ostrowski et al., 1996). The next step, presented here, was to conduct pilot release-recapture experiments to evaluate release strategies and recruitment potential of cultured Pacific threadfin. This study was conducted at nursery habitats along the windward (eastern) coast of Oahu. Differences in recapture rate of released fish were a function of release size, season, and site. This pilot study had a major effect on juvenile recruitment at one of the study sites.

Materials and Methods

Culture of Pacific Threadfin.—We spawned wild Pacific threadfin brood stock at The Oceanic Institute to produce fingerlings for release into the wild. Batches of eggs were hatched every 10 d over a 3-mo period in 1993 and over a 5-mo period in 1994. At least 30 wild females were spawned. Larvae from each batch were hatched and reared for 25 d in 4000-L raceways or 5000-L cylindrical tanks according to protocols described by Ostrowski et al. (1996). We size graded postlarvae (25 d old, 10–20 mm fork length [FL]) with a commercial bar grader to separate fish greater than and less than 15 mm FL to reduce cannibalism. Fish were then transferred to 8000-L cylindrical tanks and reared for 15 d to stage-one juveniles (30–60 mm FL, 40 d old). Stage-one juveniles were size graded and then transferred to 20,000-L cylindrical tanks and reared for 15 d to stage-two juveniles (50–80 mm FL, 55 d old). Stage-two juveniles were size graded and split into additional 20,000-L tanks, where they were reared to the sizes released (fingerlings 48–150 mm FL).

Initial Release-recapture Experiment: Effect of Release Site and Size at Release.—In 1993, a release-recapture experiment yielded preliminary data on the effects of release site and size at release (SAR) on growth and recapture rate. Three sizes and two release locations were used, and the releases were repeated three times from 2 November through 8 December, during peak juvenile recruitment season. All fish were individually tagged with both coded-wire tags and visible implant tags (Northwest Marine Technology, Inc.) that identified experimental treatment conditions. Fish were released at two sites along Oahu's northeastern coast, half at Kahana Bay and the other half at

Laie Beach (Fig. 1). Within SAR groups, replicate release lots contained roughly equal numbers of fish (Table 1).

Fish were harvested from culture tanks and transferred to 40,000-L holding tanks for tagging. During harvesting, fingerlings were crowded together with connected, mesh-panel crowders, which minimized handling of the sensitive juveniles. Crowded fish were then scooped out of the water with 15-L buckets and "wet-packed" to a transport tank. Salinity in the transport tank ranged between 25 and 28‰, which improved transfer recovery. Salinities in the nursery and holding tanks normally fluctuated between 32 and 34‰. During tagging, fish were held in floating 4-ft × 8-ft net pens that separated fish sources and size classes. Time between sorting and tagging ranged from 1 to 8 d depending on the condition of the fish and the tagging schedule.

Binary-coded-wire tags (CWT, Jefferts et al., 1963) were implanted in the snout area by an automatic injector with head molds designed and developed specifically for juvenile Pacific threadfin by Washington Department of Fish and Wildlife biologists Lee Blankenship and Dan Thompson. Size-specific head molds ensured accurate CWT placement and resulted in a tagging speed of about 1000 fish hr^{-1} per injector. Unique codes were used for each release site, release lot (date), and SAR. Fish were tagged in batches, with a different code for each site-SAR-lot combination ($2 \times 3 \times 3 = 18$ batch codes). Fish released in 1993 were divided into three size intervals: 70–100 mm, 100–130 mm, and 130–150 mm FL. (Note below that smaller fish were released in 1994: 48–70 mm, 70–100 mm, and 100–130 mm FL). The principal difference between fish in the different size intervals was age. All fish were released between 08:00 and 13:00 at release sites with bottom salinities between 30 and 35‰.

In addition to coded-wire tags, all fish released in 1993 and half those released in every treatment group in 1994 were also tagged with visible implant elastomers (Godin et al., 1995; Frederick, 1997), which externally marked fish with internal CWTs. The data for the visible tags will be reported elsewhere (Blankenship and Leber, unpubl. data).

FOLLOW-UP RELEASE-RECAPTURE EXPERIMENT: INTERACTION OF THE TIMING OF RELEASES WITH SAR AND RELEASE SITE.—In 1994, to assess a different release site and to evaluate interactive effects of release strategies on recapture rate, we released 81,225 fish. The balanced, factorial, randomized-block design included two sites, three SARs, three seasons, and three lots ($2 \times 3 \times 3 \times 3 = 54$ batch codes). The principal difference between the 1993 and 1994 experiments was the addition of release season as an experimental variable in 1994. Releases occurred at various times before and during the peak juvenile recruitment period — three during July–August ("summer"), three in September–October ("fall"), and three in November–December ("winter") (Table 2). Smaller individuals were released in 1994 (48–130 mm FL) than in 1993 (70–150 mm FL). Juveniles were size graded into three groups, tagged with both coded-wire tags and visible implant tags, and released. Releases were at Kahana Bay and Malaekahana Bay (Fig. 1). Fingerlings were harvested and tagged as described above. During both years, releases at the two sites were <1 h apart.

To verify tag-retention rates for this study, we examined a random subsample of at least 5% of the fish tagged for each SAR group within release lots before each release (fish in the subsample were in addition to the 81,225 fish actually released). The subsamples were placed in 1000-L cylindrical tanks and held for 8 mo. Tag retention was monitored monthly. Fish in the subsamples were not released.

All three release sites were juvenile Pacific threadfin habitats with sandy bottom and moderate wave energy. Kahana Bay is unique in receiving more freshwater inflow than the other two sites. Salinities in the bay were generally high (>30‰) but fluctuated between 10 and 32‰ during rainy periods. Releases at Kahana Bay were performed at a boat ramp with a release hose 30 ft long and 4 in in diameter.

Laie Beach (approximately 12 km north of Kahana Bay) does not receive inflow from freshwater streams, and salinities ranged from 32 to 35‰. The Laie release site was located along an unprotected shoreline with coral reefs patchily distributed 3–7 m beyond the sandy beach. Channels among reef patches lead out to a fringing reef 1–2 km offshore. Releases into shoreline water at Laie were performed with a hose 80 ft long and 4 in in diameter.

Table 2. Summary statistics for 81,225 fish tagged and released in 1994 for evaluation of hatchery releases in Kahana Bay and Malaekahana Bay. Unique batch codes were used to identify fish from each cell in the matrix. Summer lot 1 was released on 13 July, lot 2 on 27 July, and lot 3 on 10 August. Fall lot 1 was released on 7 September, lot 2 on 21 September, and lot 3 on 6 October. Winter lot 1 was released on 3 November, lot 2 on 17 November, and lot 3 on 1 December.

		Summer release lot				Fall release lot				Winter release lot				
Release site	Size at release	1	2	3	Total	1	2	3	Total	1	2	3	Total	Grand total
Kahana Bay	48–70 mm	985	1,494	1,283	3,762	1,211	2,069	1,779	5,059	1,225	1,879	1,237	4,341	13,162
	70–100 mm	1,117	1,886	1,111	4,114	2,926	2,083	1,804	6,813	1,967	1,234	1,136	4,337	15,264
	100–130 mm	1,726	1,481	714	3,921	957	908	1,917	3,782	2,863	646	892	4,401	12,104
	Subtotal	3,828	4,861	3,108	11,797	5,094	5,060	5,500	15,654	6,055	3,759	3,265	13,079	40,530
Malaekahana Bay	48–70 mm	855	1,478	1,203	3,536	1,215	2,084	1,786	5,085	1,242	2,160	1,292	4,694	13,315
	70–100 mm	1,218	1,874	713	3,805	2,889	2,078	1,772	6,739	2,024	1,264	1,176	4,464	15,008
	100–130 mm	2,104	1,477	728	4,309	586	974	2,000	3,560	2,840	749	914	4,503	12,372
	Subtotal	4,177	4,829	2,644	11,650	4,690	5,136	5,558	15,384	6,106	4,173	3,382	13,661	40,695
Grand total		8,005	9,690	5,752	23,447	9,784	10,196	11,058	31,038	12,161	7,932	6,647	26,740	81,225

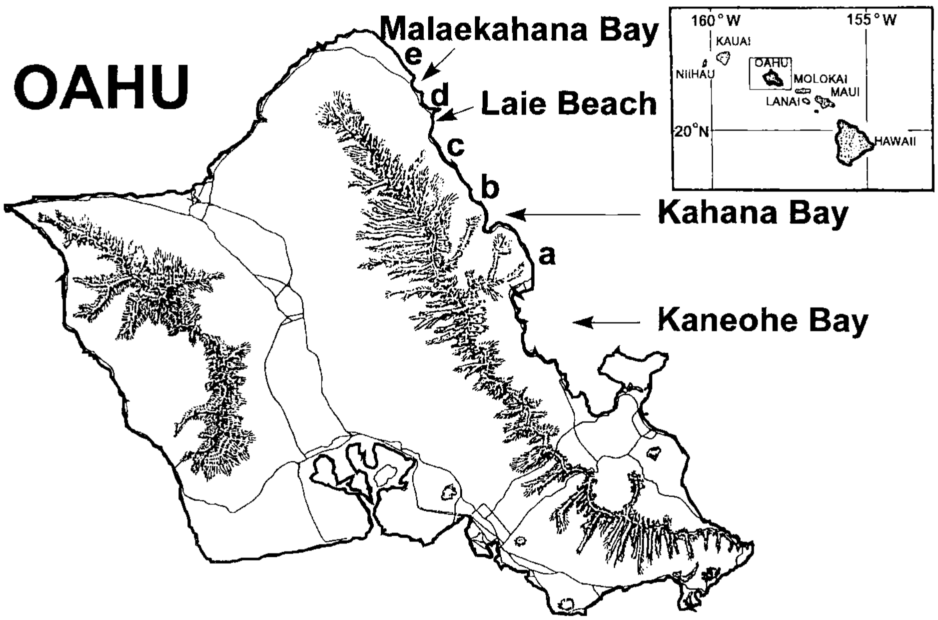

Figure 1. Map of windward coast of Oahu, Hawaii, showing pilot release sites. In this study, periodic seine collections were conducted at the three release sites and five other coastal nursery habitats (a = Kaaawa Beach; b = Punaluu Beach; c = Pounders Beach; d = Hukilau Beach; e = Kahuku Beach). Pacific threadfin releases were made at Kahana Bay, Laie Beach, and Malaekahana Bay. Kaneohe Bay was the principal release habitat on Oahu in previous release-recapture studies of cultured striped mullet.

The northern site, Malaekahana bay, was chosen to replace Laie Beach for the follow-up experiment because of poor recapture rates at Laie. Salinities were typically >32‰. Releases at Malaekahana were performed from a 2-m-high rocky cliff, from which the 80-ft hose extended down onto the beach. At all sites, releases were made into shoreline water 0.5–1 m deep. The distal end of the release hose was pointed at about a 45° angle to the surface of the water, so that fish exited the hose in air and could dive into the water.

Recapture of Tagged Juveniles.—Cultured and wild Pacific threadfin were monitored in periodic seine collections from January 1994 through May 1995. Collections were made during an 8-h daylight period at five sites after 1994 releases and at seven sites after 1993 releases (Fig. 1). Stations were established in the vicinity of Pacific threadfin nursery habitats at various locations along the northeast coast of Oahu.

For seining we used a 25-m-long beach seine, 1.8 m deep, with 1.3-cm stretch mesh and a collection bag 1.8 × 1.8 × 1.8 m. Twelve replicate seine hauls were conducted at each sampling station, because preliminary sampling indicated that that level of effort would produce abundance estimates with a coefficient of variation of <10%. Distribution of seine hauls along the beach was determined by the topography of each site. Seine hauls began seaward of the surf impact zone; seines were pulled through the surf toward the beach. Each seine haul was conducted by at least three researchers — one on each of the wings and a third keeping the central collection bag close to the substratum. Because at two sites the beach was not long enough for 12 non-overlapping seine hauls, we used two substations at each of them (Kaaawa Beach and nearby Kaoio Point formed the "Kaaawa Beach" station; Pounders Beach and nearby Mahakea Beach formed the "Pounders Beach" site). Six seine hauls were made at each of the two substations. At the other stations, the area

Table 3. Retention of coded-wire tags (CWT) after eight months in 3753 Pacific threadfin held in 5000-L tanks. Fish were subsamples from release batches selected randomly on the day of release.

Size interval		Lot 1	Lot 2	Lot 3	Lot 4	Lot 5	Lot 6	Lot 7	Lot 8	Lot 9	Totals
48–70 mm	Total fish	106	158	114	127	186	207	197	205	78	1,378
	Total CWT	94	150	110	126	183	184	186	157	76	1,266
	% tag retention	88.7	94.9	96.5	99.2	98.4	88.9	94.4	76.6	97.4	91.9
70–100 mm	Total fish	149	124	72	157	102	198	179	95	110	1,186
	Total CWT	146	119	57	154	99	190	162	74	86	1,087
	% tag retention	98.0	96.0	79.2	98.1	97.1	96.0	90.5	77.9	78.2	91.7
100–130 mm	Total fish	140	40	92	200	97	173	273	72	102	1,189
	Total CWT	126	35	84	199	91	163	256	71	93	1,118
	% tag retention	90.0	87.5	91.3	99.5	93.8	94.2	93.8	98.6	91.2	94.0

Table 4. Numbers of wild and tagged cultured Pacific threadfin recaptured in seine samples collected along the windward coast of Oahu in 1994 and 1995. Forty-nine of the 1705 cultured fish recaptured were released in November and December 1993; 48 of those were recaptured during January–June 1994. The 1994 experimental releases began in July 1994. Twelve seine hauls were made at each collection site. Sampling was discontinued at some sites after 1994 releases when recapture rate was consistently zero.

		1994								1995					
Collection site	Source	Jan	Feb	Mar	May	Jun	Aug	Oct	Dec	Jan	Feb	Mar	Apr	May	Totals
Kahuku Beach	Wild					5	0	4	0	1	27				37
	Cultured					0	0	0	0	0	0				0
	% cultured	–	–	–	–	0	0	0	0	0	0	–	–	–	0
Malaekahana Bay	Wild	0	0	76	73	5	2	6	36	21	23	24	14	14	294
	Cultured	0	0	2	1	1	132	159	217	16	19	3	2	2	554
	% cultured	0	0	2.6	1.4	16.7	98.5	96.4	85.8	43.2	45.2	11.1	12.5	12.5	65.3
Hukilau Beach	Wild	141	189	7	26	2									365
	Cultured	3	0	0	0	0									3
	% cultured	2.1	0	0	0	0	–	–	–	–	–	–	–	–	0.8
Laie Beach	Wild	36	69	13	12	2									132
	Cultured	1	0	0	0	0									1
	% cultured	2.7	0	0	0	0	–	–	–	–	–	–	–	–	0.8
Pounders +	Wild	16	20	5	2	13	2	9	62	9	11				149
Mahakea Beach	Cultured	4	0	0	0	1	3	0	2	0	0				10
	% cultured	20.0	0	0	0	7.1	60.0	0	3.1	0	0	–	–	–	6.3
Punaluu Beach	Wild	120	76	26	15	12	4	1	32	41	72	17	7	0	423
	Cultured	2	0	1	0	0	1	2	16	2	48	3	0	0	75
	% cultured	1.6	0	3.7	0	0	20.0	66.7	33.3	4.6	40.0	15.0	0	0	15.1
Kahana Bay	Wild	131	208	4	55	53	8	3	64	23	29	69	4	43	694
	Cultured	10	6	2	3	1	191	183	284	102	79	82	8	71	1,022
	% cultured	7.1	2.8	33.3	5.2	1.8	96.0	98.4	81.6	81.6	73.2	54.3	66.7	62.3	59.6
Kaaawa +	Wild	175	88	63	41	14	9	11	4	43	17	6	5	0	476
Kaoio Point	Cultured	3	2	2	3	0	1	8	1	11	9	0	0	0	40
	% cultured	1.7	2.2	3.1	6.8	0	10.0	42.1	20.0	20.4	34.6	0	0	0	7.8
Total	Wild	619	650	194	224	106	25	34	198	138	179	116	30	57	2,570
	Cultured	23	8	7	7	3	328	352	520	131	155	88	10	73	1,705
	% cultured	3.6	1.2	3.5	3.0	2.8	92.9	91.2	72.4	48.7	46.4	43.1	25.0	56.2	39.9

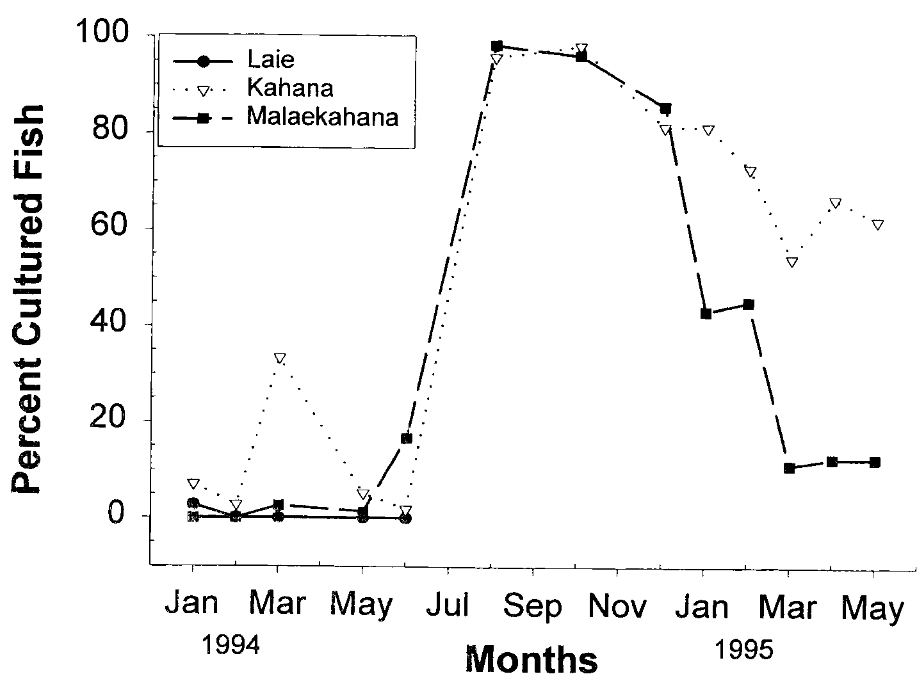

Figure 2. Percent contribution of cultured fish to Pacific threadfin abundance in seine collections. Data are percent cultured fish in Pacific threadfin collections of wild and cultured individuals at each of the three release sites. Releases began in November 1993. 1994 releases began in July and were repeated in September and November. No releases were made at Malaekahana Bay in 1993 or at Laie Beach in 1994.

sampled by the 12 seines ranged from approximately 20% (at Kahana Bay) to 60% (at Malaekahana Bay) of the shoreline.

Pacific threadfin in these collections were measured and checked for tags with a portable tag detector (Northwest Marine Technology, Inc.). Wild fish were counted, measured, and released at the sampling site. We reduced stress to wild fish by keeping them in seawater in 200-L, plastic barrels during collections. Dissolved oxygen was maintained in the barrels by air diffusers connected to oxygen canisters. All tagged fish were measured in the field and returned to the laboratory on ice for tag analysis. After extraction, the binary codes were read with a binocular microscope (40×). All tag codes were verified with a second (blind) reading by another technician.

Data were analyzed with SYSTAT software (Wilkinson, 1990). A randomized-block design ANOVA was used to compare means. Treatments (release site, SAR) were blocked over time (three release lots) within release seasons. Proportions were arcsine transformed. Orthogonal contrasts were used to compare means (Sokal and Rohlf, 1981). SYSTAT Basic was used to write tag-decoding algorithms. Variance estimates are expressed throughout as standard errors.

Results

Over the 17-mo study period, 1705 tagged Pacific threadfin were recovered in seine samples. About 2.5% (43) of the CWTs from these fish were lost during the extraction

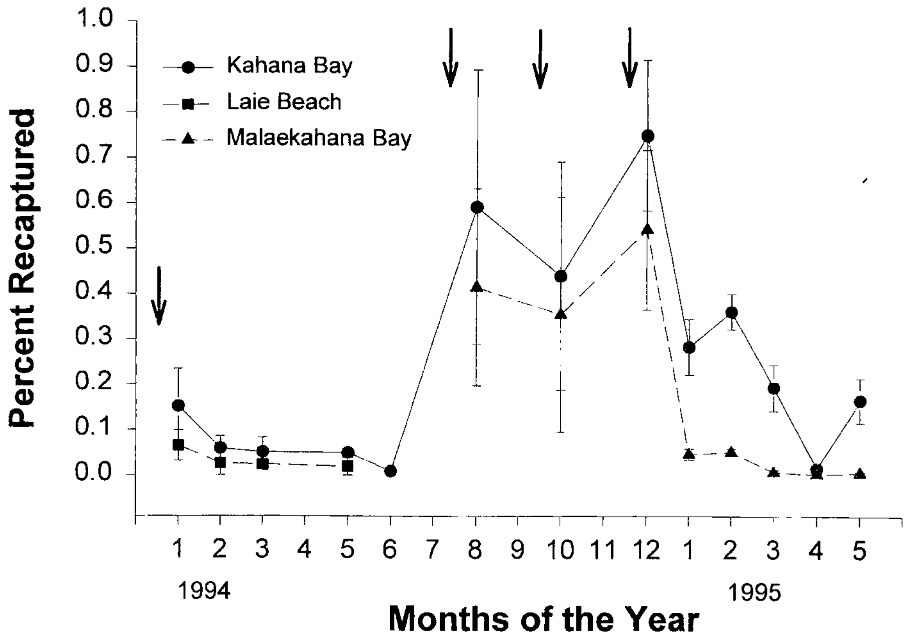

Figure 3. Release-site effect on recapture rate in seine hauls (data = (number recaptured/number released) × 100% ± SEM; n = 3 release lots). Arrows indicate release periods. No releases were made at Malaekahana Bay in 1993 or at Laie Beach in 1994. Numbers on the x-axis represent months of the year.

process. Thus, 1662 CWTs were decoded and analyzed. Of these, 46 tags were from the 1993 releases, and 1616 were from fish released in 1994. All but one of the 46 fish recovered from the 1993 release experiment were captured before the 1994 releases, which began in July.

TAG RETENTION.—During 1993 releases, 1020 cultured Pacific threadfin (in addition to the 20,010 fish released) were retained at The Oceanic Institute for monitoring of tag retention. Tag checks were performed for 8 mo after the release. Mean retention rate was 98.3%. No significant tag loss was observed in any treatment group. The 100–130-mm size class showed initial retention rates of 100%, which stabilized at 97.4% within 8 mo. This is a normal tag loss rate for CWTs (Blankenship, 1990). The 130–150-mm group had initial and final CWT retention of 100%.

In the 1994 experiment, 3753 tagged fish were retained to monitor tag retention. CWT retention was not as high in 1994; it averaged >94.0% for the largest fish released (100–130 mm), and >91.0% for the other two size groups. CWT retention ranged from 76.6 to 99.5% (Table 3).

RELEASE CONTRIBUTION TO ABUNDANCE.—This pilot release study made an unexpectedly large contribution to juvenile abundance at one of the three release sites. Cultured fish comprised less than 1% of the Pacific threadfin collected at Laie Beach, which was subsequently excluded as a release site in 1994 (Table 4). Nine months after the 1994 releases began, the percent contribution of cultured fish to juvenile recruitment remained

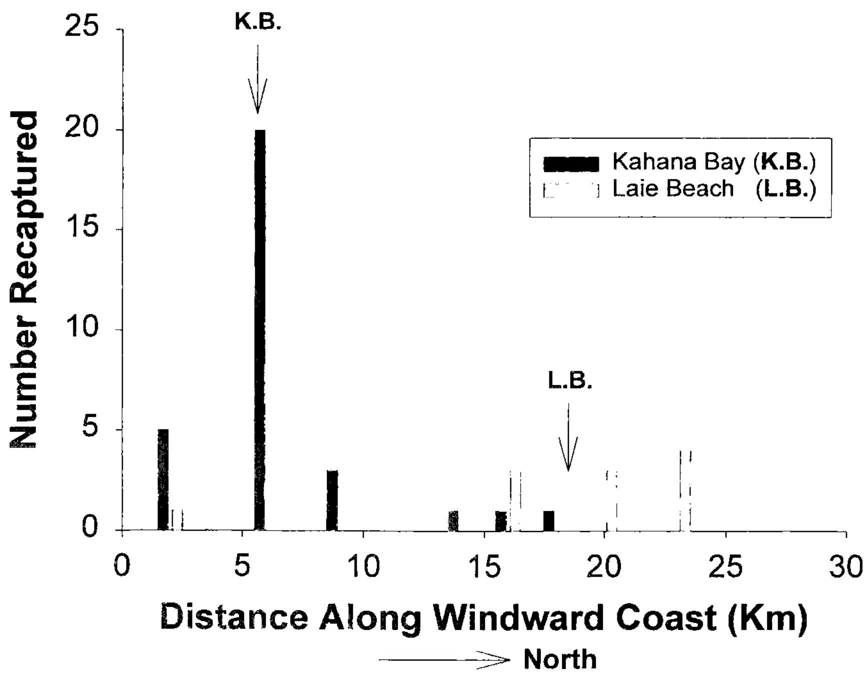

Figure 4. Dispersal after 1993 pilot release experiment. Data are numbers of Pacific threadfin recaptured during the 6-mo period following releases in 1993 at Kahana Bay (solid bars) and Laie Beach (shaded bars). The x-axis is shoreline kilometers north of Kaneohe Bay on the windward (eastern) coast of Oahu. Kahana Bay (K.B.) is approximately 6 km, and Laie Beach (L.B.) approximately 18 km, north of Kaneohe Bay.

substantial at Kahana Bay (>60%) but significantly lower at Malaekahana Bay (Fig. 2; ANOVA, $P < 0.005$ on each of the last five collection dates). Recapture rates (number recaptured/number released) were also greater at Kahana Bay than at Malaekahana Bay (Fig. 3; ANOVA, $P < 0.01$ in January, February, March, and May).

Release site affected dispersal. No fish recovered from the 1993 Laie Beach release was recaptured at the release site (Fig. 4). In contrast, a large proportion of the fish recovered from Kahana Bay and Malaekahana Bay releases were in collections made at the release sites (Figs. 4,5). Only 4% of 1079 fish recaptured after 1994 releases at Kahana Bay had moved to other sites along the coast. Only 0.5% of 537 fish recaptured after their release at Malaekahana Bay had dispersed to other collection sites.

SAR Effect on Recapture Rate.—The initial experiment, started in fall 1993, revealed a significant effect of SAR on recapture rate of cultured Pacific threadfin (Fig. 6; ANOVA, $P < 0.024$). At Kahana Bay, recapture rate was directly proportional to SAR. SAR effect was not examined for the Laie Beach releases because of the small number (12) of cultured fish recovered.

The follow-up experiment, which was repeated in summer, fall, and winter 1994 to replicate the 1993 releases and determine effects of the timing of releases, also revealed

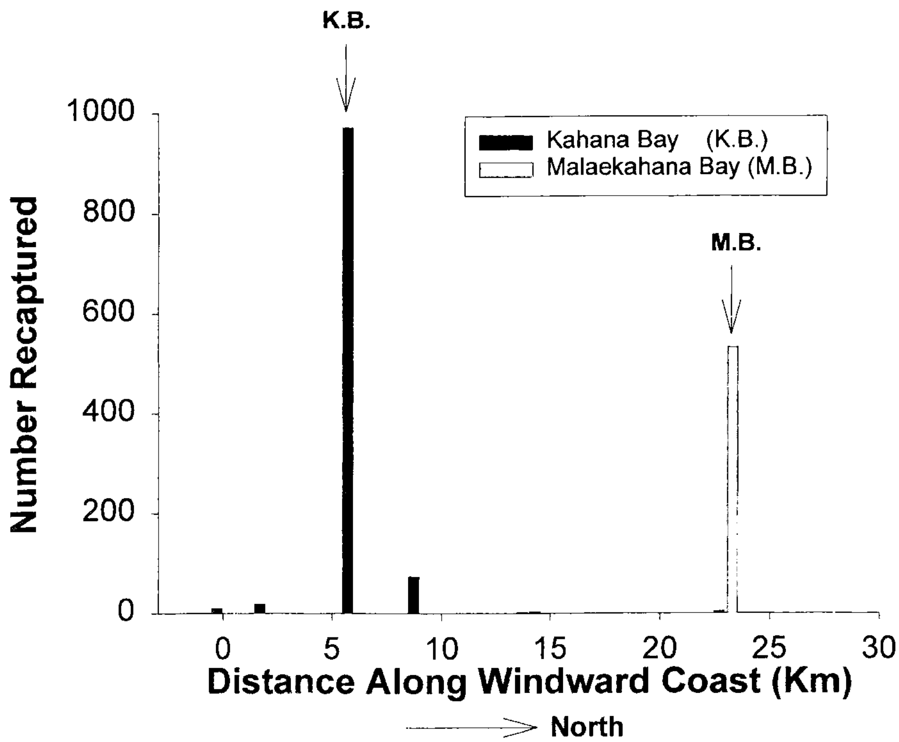

Figure 5. Dispersal after 1994 pilot release experiment. Data are numbers of Pacific threadfin recaptured during the 10-mo period following 1994 releases at Kahana Bay (solid bars) and Malaekahana Bay (shaded bars). Kahana Bay (K.B.) is approximately 6 km, and Malaekahana Bay (M.B.) 23 km, north of Kaneohe Bay on the windward coast of Oahu.

an SAR effect at Malaekahana Bay similar to the pattern after fall 1993 releases in Kahana Bay. Regardless of release season, at Malaekahana Bay recapture rate of the largest fish released (100–130 mm FL) was significantly greater than that of smaller fish released (Fig. 7; Table 5). At Kahana Bay, the winter releases in 1994 also resulted in an SAR effect similar to results at Malaekahana Bay and to results from the 1993 Kahana Bay releases (Fig. 8).

RELEASE-SEASON AND RELEASE-SITE EFFECTS ON RECAPTURE RATE.—The timing of releases directly affected size-specific recapture rates at one of the sites — there was a highly significant interaction between release season and SAR at Kahana Bay (Table 6). After summer and fall releases at Kahana Bay, recapture rates were actually inversely proportional to SAR, whereas they were directly proportional after winter releases (Fig. 8). Recapture rate of the smallest individuals released at Kahana Bay (48–70 mm) was greater in both summer and fall collections than in winter collections (ANOVA, post-hoc comparison with orthogonal contrasts, $P = 0.01$); recovery of the largest individuals released was greatest in winter collections (ANOVA, orthogonal contrasts, $P = 0.02$).

The seasonal timing of releases also appeared to affect the magnitude of recapture rates. There was a clear, but nonsignificant, trend toward relatively higher recapture rates

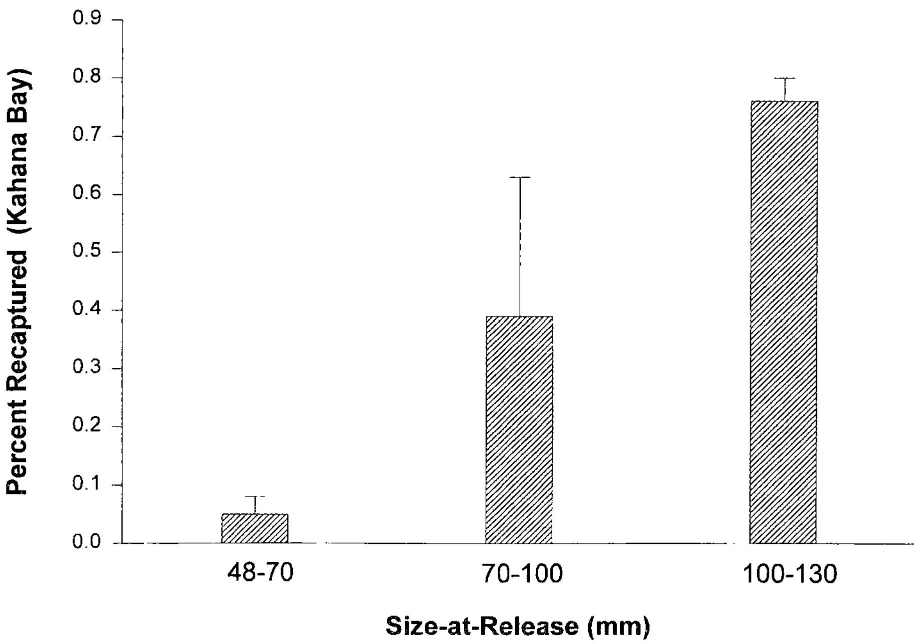

Figure 6. Recapture rates for the three sizes of Pacific threadfin released into Kahana Bay in November and December 1993. Data are mean recapture frequencies per release lot ((number recaptured/number released) × 100% ± SEM; n = 3 lots).

after releases in the fall than after either summer or winter releases at Kahana Bay and Malaekahana Bay (Figs. 7,8).

Thus, in the 1994 experiment, where release season was considered, SAR had a clear and significant effect on recapture rates. At one release site, Malaekahana Bay, recapture was directly related to SAR in all seasons. At the other site, Kahana Bay, there was also an SAR effect, but the result of that effect differed, depending upon release season: recapture rate at Kahana Bay varied directly with SAR only in winter (1993 and 1994) and varied indirectly during summer and fall.

Growth Rate.—Neither release site nor SAR affected growth rate (ANOVA; $P > 0.1$ for comparisons of growth after 16 wks in the wild; Laie release not considered because of small sample size of recovered fish). Growth was similar at the two release sites after both the 1993 and 1994 releases. Overall, growth for fish that had been in the wild >16 wks averaged 2.6 (± 1.0 SD) mm FL per week. Growth of the 70–100-mm fish released was representative of that of the other sizes released (Fig. 9).

Discussion

Effectiveness of Marine Stock Enhancement.—Debate continues over the usefulness of stock enhancement in marine ecosystems (see discussions by Stroud, 1986; Schramm and Piper, 1995; this volume). Nevertheless, resource agencies around the world are show-

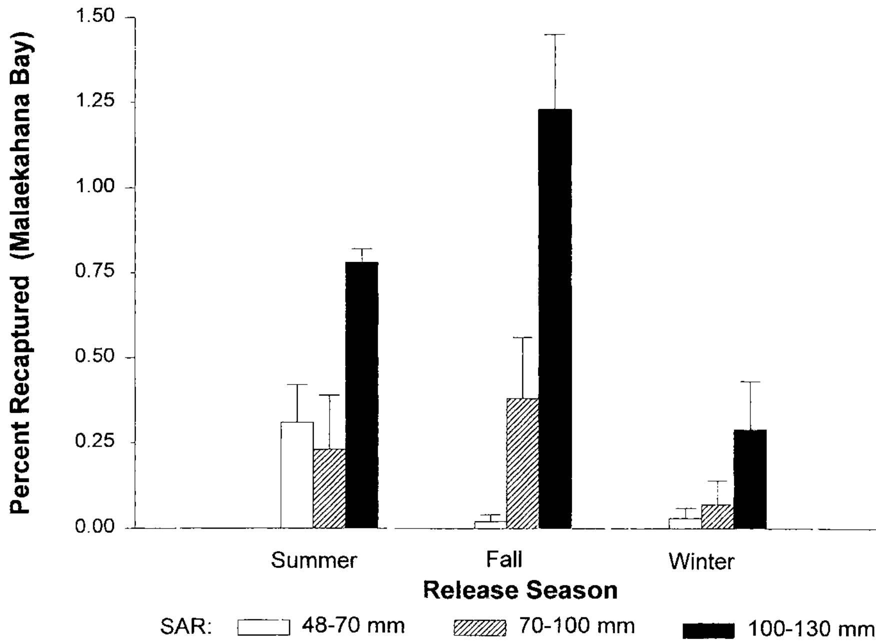

Figure 7. Recapture rates of cultured Pacific threadfin for three size-at-release (SAR) groups released at Malaekahana Bay in "summer" (July–August), "fall" (September–October), and "winter" (November–December) 1994. Data are mean recapture frequencies per release lot ((number recaptured/number released) x 100% ± SEM; n = 3 lots per season) for all fish recovered after at least 7 wks in the wild.

ing increasing interest in the potential of marine stock enhancement to help supplement and replenish depleted coastal fisheries. There should be a sense of urgency, then, to evaluate the potential of enhancing marine fish populations and whether enhancement can be carried out responsibly (Blankenship and Leber, 1995).

Quantitative assessments of the success of stock enhancement of marine fishes (that spawn in seawater) were first published in peer-reviewed scientific journals only within the past decade (e.g., beginning with studies by Tsukamoto et al., 1989; Kristiansen and Svåsand, 1990; Svåsand et al., 1990), a century after hatchery releases of marine organisms began in the U.S., Norway, and Japan. Although marine enhancement has yet to be adequately assessed in a systematic and comprehensive way (Richards and Edwards, 1986; Cowx, 1994; Blankenship and Leber, 1995), subsequent publications evaluating hatchery contributions of "hirame" flounder, *Paralichthys olivaceus,* and the scallop *Patinopecten yessoensis* in Japan (e.g., Kitada et al., 1992, 1994; Honma, 1993) and of striped mullet, *Mugil cephalus,* in Hawaii (Leber and Arce, 1996), show potential for hatchery releases to increase abundance of local spawning stocks.

Despite this potential, much uncertainty remains about whether marine stock enhancement can be a viable resource-management tool. Is stock enhancement of marine organisms a useful, yet undeveloped, technique that can help revitalize depleted wild stocks

Table 5. ANOVA table (randomized-block design, lots = blocking variable) for evaluation of release season and size-at-release effects on recapture frequencies at Malaekahana Bay after 7 wks in the wild. Data were combined here over the 20-wk period following 7 wks in the wild. Recapture frequencies are percent of the total number of fish released per lot that were recaptured during this period. These proportions were arc-sin square-root transformed before analysis.

Source of variation	Sum of squares	df	Mean-square	F-Ratio	P
Release season	0.007	2	0.004	6.666	0.007
Size at release	0.017	2	0.009	16.518	0.000
Season × size	0.005	4	0.001	2.412	0.087
Error	0.009	18	0.001		

and increase fishery yields, or are emerging marine enhancement programs likely to be no more effective than earlier attempts at marine enhancement appear to have been over most of the past century, thus diverting money and attention away from habitat restoration and the regulations needed to control overfishing? Without determined and careful attention to quantitative evaluation of enhancement impact, emerging new marine enhancement projects may serve only to fuel divisiveness among fishery scientists and have little or no positive effect on natural resources (Blankenship and Leber, 1995).

The present study adds to the emerging scientific body of evidence for evaluating the potential of marine stock enhancement to affect population size of coastal fishes. Results following releases of Pacific threadfin corroborate the hypothesis that cultured marine fishes can make a significant contribution to juvenile recruitment. The pilot releases in 1994 appear to have doubled Pacific threadfin recruitment at a primary nursery habitat, Kahana Bay. These results are similar to those following releases of striped mullet in Kaneohe Bay, Hawaii, where releases made a substantial contribution to juvenile recruitment (Leber et al., 1995, 1996, 1997), site, and ultimately to spawning stock biomass (Leber and Arce, 1996), and where release season and size at release were key factors that affected recapture rates.

A note of caution is needed here. Although the present study revealed that cultured fish can make a substantial contribution to Pacific threadfin abundance, it did not determine whether the cultured juveniles actually increased production at the study sites. More research is needed on this point. Whereas the recruitment hypothesis tested here is obviously an important first step, several other key null hypotheses must be examined experimentally in an evaluation of the effectiveness of stock enhancement. Among the most important are:

H_o: Cultured Pacific threadfin do not displace wild Pacific threadfin.

Table 6. ANOVA table (randomized-block design, lots = blocking variable) for evaluation of release season and size-at-release effects on recapture frequencies at Kahana Bay after 7 wks in the wild. Data were combined here over the 20-wk period following 7 wks in the wild. Recapture frequencies are percent of the total number of fish released per lot that were recaptured during this period. These proportions were arc-sin square-root transformed before analysis.

Source of variation	Sum of squares	df	Mean-square	F-Ratio	P
Release season	0.018	2	0.009	9.398	0.002
Size at release	0.002	2	0.001	0.988	0.392
Season × size	0.020	4	0.005	5.084	0.006
Error	0.017	18	0.001		

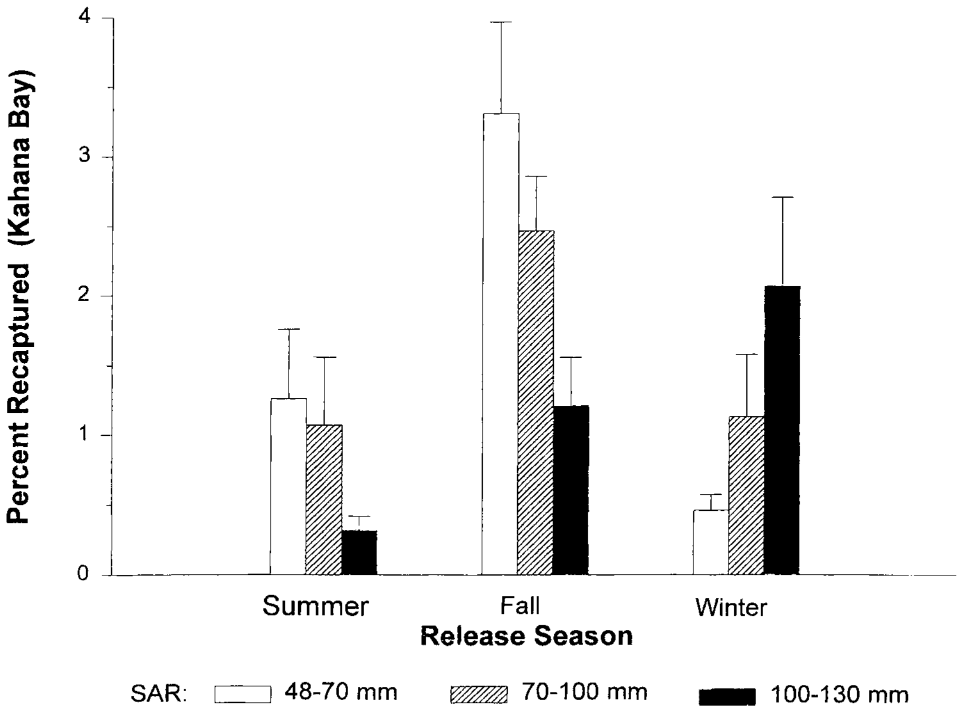

Figure 8. Recapture rates of cultured Pacific threadfin for three SAR groups released at Kahana Bay in "summer," "fall," and "winter" 1994. Data are mean recapture frequencies per release lot ((number recaptured/number released) × 100% ± SEM; n = 3 lots per season) for all fish recovered after at least 7 wks in the wild.

H_o: Genetic diversity of wild Pacific threadfin can be conserved in the stocks chosen for stock enhancement.

H_o: Health of wild stocks is not harmed by cultured Pacific threadfin.

H_o: Fishing regulations and habitat conservation cannot alone replenish wild stocks to abundance levels that could be sustained if hatchery releases were used as an additional management tool.

H_o: Release strategies (e.g., SAR, release site, season, release magnitude) are efficient.

H_o: Augmenting wild Pacific threadfin stocks with cultured fish is cost effective.

The above issues are discussed in greater detail by Blankenship and Leber (1995) and Munro and Bell (1997), along with other important considerations about evaluating and conducting stock enhancement (see Cowx, 1994).

Release Strategies.—Hager and Noble (1976) and Bilton et al. (1982) showed that release tactics were critical for survival of coho salmon (*Oncorhynchus kisutch*) released into natal streams. This finding has since been generalized to include releases into brackish water and marine environments (e.g., Tsukamoto et al., 1989; Svåsand and Kristiansen, 1990; Svåsand et al., 1990; Stoner 1994; Yamashita et al., 1994; Leber, 1995; Willis et al., 1995; Leber and Arce, 1996; Leber et al., 1996, 1997), but little work has been done with cultured organisms to test the importance of interactive effects of release strategies. Yet interaction between, for example, release season and SAR can clearly make or break

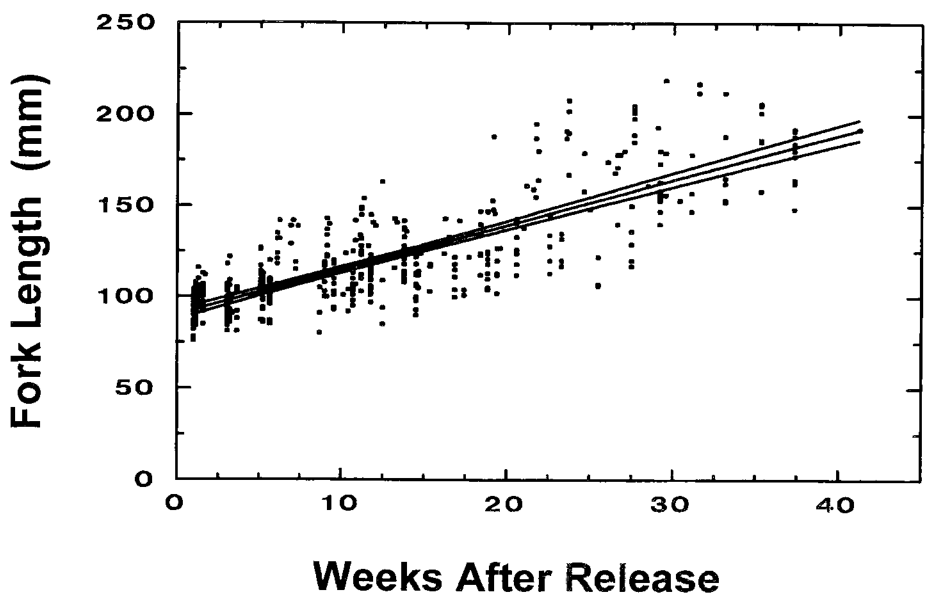

Figure 9. Scatter plot of fork length of cultured fish released in 1994 and subsequently recaptured in seine samples over a 10-mo period following releases. Data are for Pacific threadfin from the 70–100 mm FL SAR interval that were recaptured along the windward coast of Oahu from June 1994 through May 1995. Data are fitted to a linear regression with 95% confidence intervals.

release success (Bilton et al., 1982; Leber et al., 1997). These results with Pacific threadfin reemphasize our need to understand effects of release strategies before full-scale releases.

Empirical evaluation of how recruitment of released cultured fish is affected by interactions among release variables should be conducted early in the evaluation phase of stock-enhancement studies. Evaluation of such interactions will give successive release studies increasingly greater power to detect experimental treatment effects, as the efficiency of release strategies is progressively improved (Leber et al., 1996). In the absence of pilot release-recapture data, potentially effective hatchery releases could result in complete failure to affect recruitment, for example, if SAR is too small (Leber, 1995; Leber et al., 1997). Releases conducted without regard for efficiency and effectiveness of strategy risk ambiguous results and add confusion to our understanding of stock enhancement potential. Such work is counterproductive in a field of study already severely divided in its attitude toward stock enhancement (Blankenship and Leber, 1995).

Release site was clearly important in the present study and affected both dispersal and recapture rates. Cultured Pacific threadfin showed high dispersal and low site fidelity after releases at Laie Beach. Site fidelity was considerably higher at Malaekahana Bay and Kahana Bay. None of the fish recovered from the Laie Beach releases were recaptured at the release site. Recapture rates at Malaekahana Bay were low compared to those at Kahana Bay. Kahana Bay is therefore a better experimental site for future release-recapture studies with Pacific threadfin because of the higher probability of recapture there. The cause of the release-site effect on capture of released fish is unclear, but release site clearly influenced the effect of release season on SAR-dependent recapture rates (see Interactive Effects below).

SAR had significant effects on recapture after releases in both 1993 and 1994, despite the small number of 1993 fish recaptured. After 1994 releases, SAR effect was substantial at both release sites. Fall and winter releases at Malaekahana Bay would have little or no effect on recruitment if only fish <70 mm were released.

Interactive Effects of Release Tactics in This Study.—Season of release clearly affected SAR-specific recapture rates at Kahana Bay but not at Malaekahana Bay. This difference was clear after fall releases, when recapture rate was directly proportional to SAR at Malaekahana Bay but inversely proportional at Kahana Bay. Individuals <70 mm at release contributed most to recruitment (of all sizes released) in fall at Kahana Bay, yet after fall releases at Malaekahana Bay, fish <70 mm had the least (nearly undetectable) effect on recruitment.

This pattern of results at Kahana Bay was surprising. Although, in earlier studies with striped mullet, small fish released in spring showed better survival than those released in summer (Leber et al., 1997), we never saw an inverse relationship between striped mullet recapture rate and SAR.

One possible explanation for the results at Kahana Bay is sampling-gear bias (Leber and Arce, 1996; Leber et al., 1997). We expect larger Pacific threadfin to be undersampled by seines, because of their faster swimming. Survival of the fish released at larger size could therefore be even greater than our results show; future data on their contribution to the fishery will help to clarify this issue. Our results could also be caused by seasonal differences in size-specific predation and dispersal or in food availability at the two release sites. Whatever the underlying mechanism, the results are clear — SAR significantly affected recapture rates at all release sites, and release season strongly affected SAR-dependent recapture rates at Kahana Bay.

Our results have clear logistic and economic implications for stock enhancement. If the seasonal reversal in SAR effect is the typical pattern annually at Kahana Bay, and is also evident when adults are sampled, then during summer and fall, releasing small Pacific threadfin (48–70 mm) there would be considerably more cost effective than releasing larger sizes. At Malaekahana Bay, however, releasing larger fish would provide greater impact on juvenile recruitment. To determine optimal SAR and its variation with release season and release site, these data must be related to costs of rearing different sizes of Pacific threadfin (Leber and Cantrell, unpubl. data) and to yields in the fishery of the various sizes released.

Conclusions

Effectiveness of Pacific threadfin releases was strongly influenced by three variables: size at release, release season, and release site. Hatchery-release programs should always be accompanied by exploratory pilot release-recapture studies at any new sites chosen for stocking. This study revealed that the most effective size at release in one season could be the least effective in another, depending upon release site. Thus, stocking programs cannot simply generalize results from one site to another or from season to season. Rather, researchers and managers conducting stock-enhancement programs should use exploratory experiments to identify tentative release protocols. Then, the exploratory experiments should be followed by some level of ongoing evaluation of releases in subsequent years until data on annual variability in SAR-dependent recapture rates are sufficient to predict optimal SAR at each site. Studies of seasonal changes in predator densities and food availability may provide a better understanding of the mechanism controlling seasonal effects on recapture rates.

Released cultured fish made a major contribution (>50%) to recruitment of Pacific threadfin juveniles at Kahana Bay. The number of fish released in this pilot study was clearly at or above the maximum needed, given 1994 recruitment strength at Kahana Bay; had we released many more fish, young-of-the-year wild Pacific threadfin there would probably have been swamped by cultured fish. Numbers of fish released must be carefully evaluated before "full-scale" stock enhancement of Pacific threadfin, if the objective is not to exceed a certain ratio (e.g., 1:1) of cultured to wild fish.

Hatchery releases appear to have large potential to affect juvenile recruitment patterns of Pacific threadfin, so careful attention must be given to key conservation issues as we evaluate stock-enhancement potential (see Munro and Bell, 1997; Blankenship and Leber, 1995). Determining how releases will affect Pacific threadfin production will depend on further work to evaluate whether cultured fish displace or prey on wild individuals and whether the release contribution evident in this study is also apparent when released fish reach maturity. These questions, and the other issues framed as null hypotheses herein, must be addressed if we are to use hatchery releases wisely (along with fishing regulations and habitat protection) to help replenish Pacific threadfin in Hawaii.

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