North American Journal of Fisheries Management 25:1596–1608, 2005

DOI: 10.1577/M04-093.1

[Article]

Optimizing Cost-Effectiveness of Size at Release in Stock Enhancement Programs

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Abstract.—In this paper, we consider how size at release (SAR)−dependent survival of stocked fish can influence the cost-effectiveness of stocking strategies. Production costs for various sizes of juvenile fish were related to performance based on capture rates in a subsistence fishery in Kaneohe Bay on the island of Oahu, Hawaii. Using production cost data from a small-scale research hatchery, we examined the costs required to rear striped mullet *Mugil cephalus* to various stocking sizes. A spreadsheet cost model for marine shrimp aquaculture was adapted to striped mullet intensive culture techniques in Hawaii. Costs were calculated for the maturation, hatchery, and nursery phases of striped mullet production based on spawning protocols that reflected conservation of wild-stock genetic diversity. We identified the costs required to rear fingerlings to each of five consecutive size intervals, ranging from 45 to 130 mm total length (TL). Size-dependent postrelease mortality had a significant impact on the cost-effectiveness of stocking strategies. A simple mathematical model was developed to determine the optimal (most cost-effective) SAR for a stock enhancement program that releases striped mullet into Kaneohe Bay. The production-related cost of an enhancement effect (dollars spent in the hatchery to achieve a hatchery fish contribution to the fishery) was least for fish that were 85–110 mm TL when stocked. These kinds of empirical data from pilot hatchery release studies should be factored into decisions about the sizes of fish released in stocking programs.

A half century ago, hatcheries established in the USA to supplement marine fish stocks were abandoned for lack of evidence of impact (Richards and Edwards 1986). Worldwide declines in coastal fisheries have sparked a resurgence of interest in hatchery-based marine stock enhancement (see symposium proceedings edited by Lockwood 1991; Danielssen et al. 1994; Travis et al. 1998; Howell et al. 1999; Leber et al. 2004).

New marine aquaculture capabilities coupled with advances in tagging technology and demands for fiscal, conservation, and scientific accountability in fisheries management have fostered a more quantitative approach to stock enhancement (Cowx 1994; Blankenship and Leber 1995; Munro and Bell 1997). Contemporary research in this field is evaluating and quantifying hatchery release impact and is beginning to address critical uncertainties in stock enhancement theory.

It is obvious that the survival of cultured fishes that are released (stocked) into coastal ecosystems is partially mediated by the size of individuals at the time of release into the wild (Hager and Noble 1976; Tsukamoto et al. 1989; Svåsand and Kristiansen 1990; Yamashita et al. 1994; Leber 1995). In spite of the evidence that performance of stocked fish is strongly affected by fish size at release (SAR), few stocking programs have identified which SAR is the most cost-effective stocking strategy. This is not surprising, for despite a long history of hatchery releases in marine environments, the economic performance of stocking programs has not received much attention (Hilborn 1998). There is little empirical information about cost–yield dynamics in the marine stock enhancement literature. Most of the work on this subject has been conducted in Japan, where a major gov-

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Received June 17, 2004; accepted June 17, 2005

ernment investment has been made in coastal stock enhancement (e.g., Kitada et al. 1992; Sproul and Tominaga 1992; Ungson et al. 1993).

In this paper, we consider how SAR-dependent survival of an estuarine fish can affect the cost-effectiveness of stocking strategies used in stock enhancement pilot studies in Hawaii. Clearly, there are many factors besides SAR that affect the survival of stocked fish and the effectiveness of stocking (e.g., release habitat, release timing, release season, acclimation, economic value of the fishery, etc), but those issues are well beyond the scope of this study. Here, we isolate the effects of SAR on the cost-effectiveness of stocking to query whether hatchery programs should evaluate empirically a broad range of fish sizes before selecting which size seems the most economical to stock.

Methods

Following several pilot studies to evaluate the survival of cultured age-0 striped mullet *Mugil cephalus* released into juvenile nursery habitats in Hawaii, a subsistence striped mullet fishery was sampled to identify the proportions of hatchery fish in the baywide catch (Leber and Arce 1996). All cultured striped mullet that were stocked in Hawaii were tagged to identify release (stocking) variables. The pilot studies, conducted at the Oceanic Institute, Waimanalo, were part of an ongoing research program established to evaluate the potential use of marine stock enhancement for helping replenish depleted fish stocks in Hawaii. In those studies, recapture rates were directly related to SAR. Tag data from hatchery fish recovered in the fishery (Leber and Arce 1996) are linked here to 1993 fish production cost data to identify the economically optimal SAR.

Effect of SAR on capture frequency in the fishery.—Recovery data for hatchery fish landed in a small subsistence striped mullet fishery in Kaneohe Bay, Hawaii, can be compared among SAR intervals based on direct sampling of the striped mullet catch (Leber and Arce 1996). In the study by Leber and Arce (1996), a sampling program designed to recover cultured striped mullet from the striped mullet fishery resulted in the recovery of 214 tagged hatchery fish. The effects of SAR on recapture frequency were determined based on tag information from the recaptured hatchery fish. The hatchery fish were released in pilot studies discussed below and were subsequently caught in the striped mullet fishery during 1993 and 1994 (Leber and Arce 1996).

The cultured fish were produced from multiple spawns of wild parental stock at the Oceanic Institute and were reared to various sizes, ranging from 45 to 130 mm total length (TL). Five size intervals were produced in the hatchery (45–60, 60–70, 70–85, 85–110, and 110–130 mm TL). A randomized-block experimental design was used to evaluate effects of release strategy on recapture rate. Each fish was identified with a binary-coded wire tag (Jefferts et al. 1963) and released during 1990–1992 pilot experiments in Kaneohe Bay (Leber 1995; Leber et al. 1995, 1996, 1997). Detailed descriptions of the tagging and release methods are presented in those papers. Kaneohe Bay is located on Oahu's windward (eastern-facing) coast. Leber and Arce's (1996) methods are discussed below for evaluating the SAR effect on recruitment of hatchery fish to the fishery during 1993 and 1994.

The striped mullet fishery, which is closed to fishing during the winter spawning season, was sampled during spring, summer, and autumn in both 1993 and 1994. Effort was focused in two directions: (1) sampling of the Kaneohe Bay striped mullet catch sold in local fish markets and (2) direct sampling of the fishery in Kaneohe Bay (Leber and Arce 1996).

Discussions with local fish market owners resulted in their cooperation in allowing Leber and Arce (1996) to conduct weekly sampling of the local striped mullet brought to their markets. Maintaining regular contact with fish market owners also expanded the list of identified striped mullet fishermen in the bay, as a trusting relationship was developed with the owners (Leber and Arce 1996).

Direct contacts were made with striped mullet fishermen in Kaneohe Bay to elicit their cooperation. Technicians working with Leber and Arce (1996) then either participated as crew in fishing excursions and sampled the striped mullet catch in situ or waited at the dock and sampled the catch. This generated data on gear type, effort, total catch per trip, fish lengths, and proportions of cultured and wild fish caught. These samples also provided data on percent contribution of cultured fish in the catch and tag data from each of the hatchery fish. Weekly sampling was conducted during the open fishing season, beginning in March and continuing through November in 1993 and 1994. The fishery used surround nets, gill nets, and cast nets. Hatchery fish were detected by sampling the catch with a field sampling detector (Northwest Marine Technology, Inc., Shaw Island, Washington) used to detect coded wire tags. All tagged fish were supplied without cost when project staff worked as crew on board vessels; otherwise, dockside price was paid for tagged fish (Leber and Arce 1996).

The recovered hatchery fish were placed on ice and returned to the laboratory, where tags were extracted. Tags were decoded by use of a binocular microscope (40×). To verify tag codes, each tag was read twice by separate technicians. SYSTAT Basic (Wilkinson 1990) was used to write tag decoding algorithms. For each recaptured fish, tag codes identified release date, batch size, release lot, release site, and SAR (Leber and Arce 1996). Recapture frequencies were determined by averaging recovery rates (i.e., number recaptured/number released) within release lots, release sites, and SAR intervals.

Production costs.—We estimated unit production costs for juvenile striped mullet by modifying an electronic spreadsheet model that was originally developed for the financial analysis of shrimp aquaculture production systems (Leung and Rowland 1989). The model is composed of four interrelated but separate operation modules: maturation, hatchery, nursery, and grow out (Leung et al. 1993; Kam et al. 2002). Each operation module contains worksheets for input and calculation of the following categories: product, feed, labor, capital, operating costs, and other. In addition, the hatchery section includes worksheets for production of phytoplankton, rotifers, and brine shrimp *Artemia* spp. A financial module integrates these operations and provides an overall financial evaluation. The generalized nature of the model makes it adaptable to finfish production systems, and the modular format allows for evaluation of various production phases.

The original Leung and Rowland (1989) model was modified for the analysis of marine finfish production systems in at least two other studies. Leung et al. (1993) adapted the original model to simulate the cost and profitability of producing striped mullet fry based on a proposed commercial hatchery design. The Leung et al. (1993) model incorporated only the maturation and hatchery modules of the original model. More recently, Kam et al. (2002) developed a spreadsheet model, which was based on the original Leung and Rowland (1989) model, to determine the viable scale for a commercial hatchery producing Pacific threadfin *Polydactylus sexfilis* in Hawaii. The Kam et al. (2002) model incorporated spawning, larval rearing, and early nursery phases to determine the unit cost of producing 1.00-g fry on a commercial basis.

Both the Leung et al. (1993) and Kam et al. (2002) models estimate the fixed and variable costs associated with construction and operation of commercial finfish aquaculture production facilities. Because the facilities used for rearing striped mullet in our analysis were part of an existing multiuse research facility, we did not attempt to estimate fixed costs. Our unit cost estimates are based on (1) direct project costs, such as wages and benefits of research personnel, energy for source water pumps and blowers, and materials and supplies used in the project, and (2) facilities and administrative charges for building and equipment use, maintenance, and financial administration (including purchasing and accounting). Facilities and administrative charges are calculated as 87% of wages and benefits in this analysis. The resulting model specifies production costs associated with the use of existing research facilities, established culture methods, and hatchery spawning guidelines that prevent inbreeding and outbreeding depression as recommended by Kapuscinski and Jacobson (1987), Shaklee et al. (1993), and Busack and Currens (1995).

Production system.—The production system used in this analysis includes a maturation phase, a hatchery phase, an intensive nursery phase, and an extended nursery or grow-out phase. The system incorporates procedures that were developed for striped mullet production at the Oceanic Institute (Eda et al. 1991; Lee and Kelley 1991; Ako et al. 1994; Tamaru et al. 1994;). We estimated that one production run would be required to produce 90,000–94,000 juvenile striped mullet in any of the five SAR intervals.

The maturation phase of production includes broodstock acquisition and spawning. All broodstock were wild caught and had undergone acclimation and conditioning in land-based tanks. The spawning phase of production uses 8 female and 16 male broodfish. Assuming that at least 50% of the broodstock population will spawn during a designated period, this scenario requires 16 female and 32 male broodfish. It is assumed that each female will produce between 200,000 and 700,000 eggs with a fertilization rate of at least 75%. A total of 480,000 eggs, or 60,000 viable eggs from each of the eight females spawned, are required for this scenario. The large number of spawners but relatively small proportion of eggs used from each spawn follows established protocols in accordance with responsible genetic guidelines for stock enhancement. This is designed to achieve the allele frequencies necessary for conserving rare alleles in the population and for avoiding genetic selection in the hatchery.

For the hatchery phase, viable eggs are stocked directly into four 5,000-L (4,000-L working volume) larval rearing tanks at a density of 30 eggs/L, or 120,000 eggs/tank. A hatch rate of 83% leaves a posthatch stocking density of about 100,000 larvae/tank. A conservative survival rate of 30% will produce 30,000 postlarvae/tank or 120,000 postlarvae/run. The mean size at harvest is 20 mm TL. The rate of survival used in this analysis (30%) for the hatchery phase of production was based on numerous trials conducted to produce postlarval striped mullet for stock enhancement research. Previous experiments at the Oceanic Institute resulted in survival rates as high as 71% (Ako et al. 1994). However, we used the more conservative survival level here because it was the realized mean survival rate gained from multiple production runs. If the greater survival levels can be achieved on a regular basis during production runs, the stated costs in this paper would decrease.

The hatchery phase is supported by culture of live feeds. The microalga *Nannochloropsis oculata* is used to support culture of the rotifer *Brachionus plicatilis*. Pure stock cultures are progressively scaled up to harvestable volumes of 20,000 L. This scenario requires an indoor algae room large enough for stock cultures and outdoor facilities composed of four 500-L, four 5,000-L, and three 20,000-L tanks. Harvest density is 2×10^7 cells/mL. The rotifer is cultured by means of a 48-h ‘‘batch’’ culture system. Rotifer production requires twelve 1,200-L cylindrical fiberglass tanks. The system has a production capacity of 9.6×10^8 rotifers/d. About a third of this total is used for inoculation of rotifer cultures, and two-thirds is available for striped mullet larval rearing. From day 2 to day 25 posthatch, rotifers are provided to larvae at a variable rate; the maximum daily requirement occurs from day 17 to day 25. Production of *Artemia* spp. nauplii requires four 300-L fiberglass tanks. A hatching period of 24 h is followed by a 24-h enrichment period. The enrichment process is used to significantly elevate all of the fatty acids found in the nauplii. *Artemia* are fed to striped mullet larvae from day 17 to day 30 at a variable rate, and the maximum daily requirement occurs from day 25 to day 30. Weaning of striped mullet larvae to dry feed starts at day 25. Commercial feed is introduced at a size of 150 μm and is gradually increased in size as the larvae increase in size.

The intensive nursery phase uses six 5,000-L (4,000-L working volume) tanks. Postlarvae are stocked at an initial rate of 20,000 fish/tank (5 fish/L). The total number stocked in six tanks is 120,000 fish. A survival rate of 80% will produce 16,000 juveniles/tank or 96,000 juveniles/run. This phase lasts for 30 d, and the mean size at harvest is 40 mm TL.

The extended nursery phase uses four 30,000-L (20,000-L working volume) tanks. Juveniles are initially stocked into two tanks at a density of 48,000 fish/tank (2.4 fish/L), and then are split into four tanks as they grow larger. The total number stocked is 96,000 fish. The length of the extended nursery phase varies based on the desired SAR. The total number produced in each SAR interval is adjusted to reflect a mortality rate of 1–2% during each interval. Rearing fish to the 45–60-mm-TL SAR interval requires an extended nursery phase of 25 d and produces a total of 94,080 juveniles. Rearing fish to the 60–70-mm SAR interval requires an extended nursery phase of 45 d and produces a total of 93,139 juveniles. Rearing fish to the 70–85-mm SAR interval requires an extended nursery phase of 70 d and produces a total of 92,208 juveniles. Rearing fish to the 85–110-mm interval requires an extended nursery phase of 114 d and produces a total of 91,286 juveniles. Rearing fish to the 110–130-mm interval requires an extended nursery period of 150 d and produces a total of 90,373 juveniles.

Modeling of recapture rate.—We simply postulate that recapture rate (R) is a function of release size (S), release location (LOC), release lot (LOT), and release season (SEA). The main focus here is to describe the relationship between R and S. The factors (other than S) chosen to explain the variation in R are the obvious ones that are recorded. In particular, the following relationship is considered for empirical estimation:

$$R = \beta_0 + \beta_1 S + \beta_2 S^2 + \beta_3(\text{LOC}) + \beta_4(\text{LOT}) + \beta_5(\text{SEA}) + \varepsilon, \qquad (1)$$

where LOC, LOT, and SEA are sets of dummy variables.

Since the dependent variable of R is censored at zero, conventional regression models will produce inconsistent and inefficient estimators (Maddalla 1992). The Tobit model is appropriate in this case, as it accounts for the censored distribution of the error terms due to observations of R equal to zero. The structure of the Tobit model in this analysis can be expressed as

TABLE 1.—Estimated cost (US$) of rearing juvenile striped mullet to each of five size-at-release (SAR) intervals for pilot-scale releases in Hawaii (these data were used in equations 4 and 5). Percentages represent percent of total (direct plus indirect) costs.

	SAR interval (mm TL)				
	45–60		60–70		70–85
Cost	$	%	$	%	$
Direct costs					
Broodstock acquisition	720	1.89	720	1.69	720
Feed	1,402	3.67	1,737	4.07	2,303
Energy	1,349	3.53	1,592	3.73	2,065
Supplies	1,525	3.99	1,525	3.57	1,725
Other	1,569	4.11	1,569	3.67	1,711
Wages and benefits	16,906	44.28	19,027	44.54	21,136
Total	23,471	61.48	26,170	61.25	29,660
Indirect costs					
Facilities and administration[a]	14,708	38.52	16,553	38.75	18,388
Total costs	38,179	100.00	42,723	100.00	48,048
Cost per juvenile (1994 US$)	0.41		0.46		0.52

[a] Facilities and administrative charges were calculated as 87% of wages and benefits.

$$R^* = \beta_0 + \beta_1 S + \beta_2 S^2 + \beta_3(\mathrm{LOC}) + \beta_4(\mathrm{LOT}) + \beta_5(\mathrm{SEA}) + \varepsilon, \tag{2}$$

where $\varepsilon \sim N(0, \sigma^2)$ and R^* is a latent variable that is observed for values greater than zero and is censored for values less than or equal to zero. In other words, there is a latent variable R^* that is observed only when its value is greater than a certain threshold:

$$R = \begin{cases} \beta_0 + \beta_1 S + \beta_2 S^2 + \beta_3(\mathrm{LOC}) \\ \quad + \beta_4(\mathrm{LOT}) + \beta_5(\mathrm{SEA}) + \varepsilon \\ \qquad \text{if } R^* > 0 \\ 0 \qquad \text{if } R^* \le 0. \end{cases} \tag{3}$$

Determination of optimal SAR.—This section describes a simple mathematical model developed to determine the optimal SAR for a stock enhancement program. Without loss in generality, it is assumed that (1) the unit cost of hatchery-reared fry, C, is a function of S only, (2) R is a function of S only, and (3) other factors as described in equation (1) are assumed constant. Recapture rate R is a proxy for survival and measures relative survival only. The production-related cost of an enhancement effect, CE (i.e., dollars spent in the hatchery to achieve a hatchery fish contribution to the fishery), can simply be expressed as

$$\mathrm{CE}(S) = C(S)/R(S). \tag{4}$$

Taking the derivative of equation (4) with respect to S and setting it equal to zero yields the following first-order condition for minimum production cost of enhancement:

$$C'(S)/R'(S) = C(S)/R(S). \tag{5}$$

Equation (5) indicates that the optimal SAR to minimize cost can be determined when the marginal cost of increasing one unit of R by increasing S is equal to the average cost at that size.

Results

Production Costs

The estimated costs of producing 90,000–94,000 striped mullet juveniles in each of five SAR intervals are outlined in Table 1. Direct costs are estimated to be 61–63% of total costs. The major direct cost item, wages and benefits, accounts for 43–44% of total costs. Broodstock acquisition, feed, energy, supplies, and other combined account for 17.7% of total costs. Facilities and administrative costs account for 37–39% of total costs. The cost of rearing 94,080 fingerlings to the 45–60-mm SAR interval is US$38,179 or $0.41 per fish. The cost of rearing 93,139 fingerlings to the 60–70-mm SAR interval is $42,723 or $0.46 per fish. The cost of rearing 92,208 fingerling striped mullet to the 70–85-mm SAR interval is $48,048 or $0.52 per fish. The cost to rear 91,286 fingerlings to the 85–110-mm SAR interval is $54,974 or $0.60 per fish. The cost to rear 90,373 fingerling striped mullet to the 110–130-mm SAR interval is $65,998 or $0.73 per fish.

TABLE 1.—Extended.

	SAR interval (mm TL)				
	70–85	85–110		110–130	
Cost	%	$	%	$	%
Direct costs					
Broodstock acquisition	1.50	720	1.31	720	1.09
Feed	4.79	3,314	6.03	4,173	6.32
Energy	4.30	2,538	4.62	2,840	4.30
Supplies	3.59	2,504	4.55	3,000	4.55
Other	3.56	2,050	3.73	2,772	4.20
Wages and benefits	43.99	23,448	42.65	28,071	42.53
Total	61.73	34,574	62.89	41,576	63.00
Indirect costs					
Facilities and administration[a]	38.27	20,400	37.11	24,422	37.00
Total costs	100.00	54,974	100.00	65,998	100.00
Cost per juvenile (1994 US$)		0.60		0.73	

Recapture Frequencies

The numbers of fish released during 1990–1992, number of replicate releases within release seasons, and SAR intervals are presented in Table 2. Within seasons, five size intervals were released. Within size intervals, fish were released in *N* replicate lots. With the exception of the largest SAR interval (110–130 mm), the number of fish tagged and released per size interval ranged within seasons from approximately 11,000 to 38,000. Considerably fewer fish in the largest size interval were available for release (Table 2). The primary difference in individuals among size intervals was age (Leber 1995; Leber and Arce 1996).

Recapture frequencies for cultured striped mullet recovered from the fishery in Kaneohe Bay, Hawaii, during 1993 and 1994 are presented in detail in Leber and Arce (1996). Those recapture frequencies, which describe fish that were released during 1990–1992, are summarized here and presented in Figure 1. These data showed a significant effect of SAR on recovery of hatchery fish from the striped mullet fishery. Recovery of fish that were smaller than 60 mm TL when released was very poor relative to recovery of fish that were larger when released, particularly when releases were conducted in summer (Figure 1). These recapture frequencies, based on tag data from the hatchery striped mullet caught in the fishery, re-

TABLE 2.—Numbers of cultured striped mullet juveniles tagged and released into Kaneohe Bay, Hawaii, during 1990–1992 pilot releases.

Release season	Release size (mm TL)	Number of lots	Number of fish released
Spring	45–60	12	26,556
	60–70	12	26,706
	70–85	12	22,066
	85–110	12	10,979
	110–130	12	4,105
Summer	45–60	8	12,995
	60–70	8	15,108
	70–85	14	37,610
	85–110	14	24,450
	110–130	13	2,423

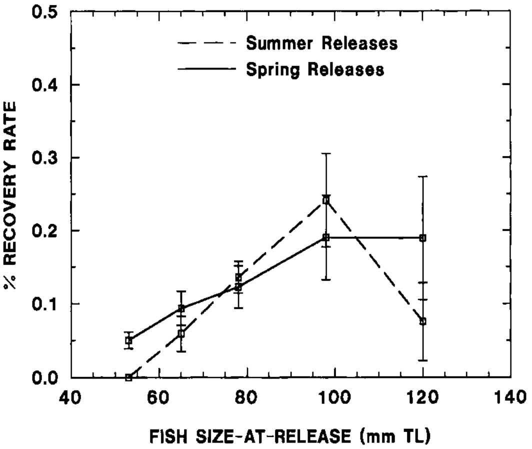

FIGURE 1.—Relationship between mean percent recovery rate ([number recaptured/number released] × 100) and fish size at release (SAR) for 214 cultured striped mullet recovered from the fishery in Kaneohe Bay, Hawaii. This plot uses the medians of the five SAR treatment groups: 45–60, 60–70, 70–85, 85–110, and 110–130 mm TL. Table 2 shows the number released and number of replicates within SAR intervals. Mean size at capture was 368 mm (14.5 in) TL and 466 g (1.03 lb). Median size at capture was 369 mm and 462 g.

flected a survival pattern quite like that seen when hatchery-released age-0 striped mullet juveniles were sampled in their nursery habitats in Kaneohe Bay and Maunalua Bay (on Oahu's south shore) over an approximately 9-month period after releases in summer (Leber 1995; Leber et al. 1996, 1997). The SAR has also been shown to have a direct effect on recapture rates of other stocked marine fishes: for example, red sea bream *Pagrus major* (Tsukamoto et al. 1989), Atlantic cod *Gadus morhua* (Svåsand and Kristiansen 1990), Japanese flounder *Paralichthys olivaceus* (Yamashita et al. 1994), Pacific threadfins (Leber et al. 1998), and red drum *Sciaenops ocellatus* (Willis et al. 1995; Smith et al. 1997). However, a stronger seasonal effect was evident when SAR effects were compared for spring versus summer juvenile releases (Leber et al. 1996, 1997) than was apparent in the adult striped mullet data collected from the fishery (Leber and Arce 1996). In the Leber et al. (1996, 1997) studies of juvenile recapture rates, spring releases resulted in little SAR effect, whereas fish released in summer showed a strong SAR effect on recapture rates (and, presumably, on survival). The pattern in Leber and Arce's (1996) data from the fishery suggests that SAR effects continued to affect striped mullet survival even after the fish migrated out of nursery habitats and into Kaneohe Bay.

Empirical Results of the Tobit Regression of Recapture Rate and Size

Based on the recovery data for cultured striped mullet that were landed in the Kaneohe Bay fishery during 1993–1994 (Leber and Arce 1996), the following Tobit regression equation was estimated:

$$\begin{aligned} R = {} & \underset{(3.93)}{-0.0159234} - \underset{(0.67)}{0.0003782\mathrm{DS1}} \\ & - \underset{(3.47)}{0.0023614\mathrm{DS2}} + \underset{(0.75)}{0.0004129\mathrm{DL1}} \\ & - \underset{(0.73)}{0.0004146\mathrm{DL2}} + \underset{(1.32)}{0.0006122\mathrm{DS}} \\ & + \underset{(4.21)}{0.0003908S} - \underset{(4.01)}{0.0000021S^2}, \end{aligned} \tag{6}$$

where R = recapture rate; DS1 = release location dummy variable (release sites = Kahaluu and Kaneohe inlets and Kahaluu Lagoon; DS1 represents Kahaluu Inlet and DS2 represents Kaneohe Inlet, and Kahaluu Lagoon is the reference site; thus, DS1 = 1 if released in Kahaluu Inlet, 0 otherwise); DS2 = release location dummy variable (DS2 = 1 if released in Kaneohe Inlet, 0 otherwise); DL1 = release lot dummy variable (there are three release lots, and lot 3 is the reference lot; thus, DL1 = 1 for lot 1, 0 otherwise) ; DL2 = release lot dummy variable (DL2 = 1 for lot 2, 0 otherwise); DS = release season dummy variable (DS = 1 for spring release, 0 otherwise); S = release size; and S^2 = the square of release size (t-ratios are shown in parentheses; SE = 0.0021963; log likelihood = 294.72, P-value = 0.0000; 48 censored observations, 69 uncensored observations).

As shown in equation (6) above, release size has a significant effect on recapture rate and the effect appears to taper off at larger sizes, as indicated by the negative coefficient of S^2. Other than DS2 showing a significantly lower recapture rate, there seems to be no significant differences between seasons, release lots, and release locations. The following Tobit regression equation is estimated by dropping the nonsignificant variables:

$$\begin{aligned} R = {} & \underset{(3.94)}{-0.0154462} - \underset{(3.82)}{0.0021301\mathrm{DS2}} \\ & + \underset{(4.10)}{0.0003814S} - \underset{(3.89)}{0.00000205S^2} \end{aligned} \tag{7}$$

(SE = 0.0022519; log likelihood = 292.34, P-value = 0.0000; 48 censored observations, 69 uncensored observations). Equation (7) shows that effect of release size on recapture rate is very similar to that of equation (6); all the estimates were significant at the 5% level. Equation (5) is used in determining the optimal SAR in the following analysis.

Empirical Results of the Relation between Production Cost and Size

Based on the estimated cost to raise various sizes of striped mullet fry in the hatchery, the following cost equation was estimated:

$$\begin{aligned} C = {} & \underset{(36.87)}{0.263} + \underset{(11.89)}{(2.05 \times 10^{-3})S} \\ & + \underset{(15.47)}{(1.52 \times 10^{-5})S^2}, \end{aligned} \tag{8}$$

for which R^2 = 0.998.

Optimal SAR

By substituting equations (7) and (8) into equation (5), the optimal SAR that minimizes cost can be determined. A spreadsheet model was created to solve for optimal SAR by use of Excel Solver. Optimal size was 88.41 mm for releases at Kahaluu Inlet and 92.69 mm for releases at Kaneohe Inlet. Whereas the fit of the production cost regression equation was very tight, we were concerned about the precision of the estimated Tobit regression equation for recapture rate, as indicated by the relatively large SEs. A sensitivity analysis based on the estimated SEs indicated that optimal size was not very sensitive to the relatively imprecise estimates of recapture rate. In fact, when the estimated recapture rate was assumed to be plus two standard deviations from the mean, the optimal SAR was calculated to be 79.61 mm for releases at Kahaluu Inlet and 83.72 mm for releases at Kaneohe Inlet. Sensitivity in the other direction caused the recapture rate to become negative. However, we were only interested in positive recapture rates as portrayed by the Tobit regression model; the optimal release size at a recapture rate close to zero was 93.01 mm for releases at Kahaluu Inlet and 98.21 mm for releases at Kaneohe Inlet. Thus, the optimal SAR was rather insensitive to the relatively imprecise Tobit estimate of recapture rate.

Production Cost per Recruit

Based on the production and cost data in Table 1, fish production costs in the hatchery were distributed across fishery recruitment levels for hatchery fish, assuming a release of 91,286 individuals in the optimal SAR interval, 85–110 mm TL (Figure 2). Figure 2 models hatchery production cost per fish landed for fishery recovery values ranging from 2% to 100% (of 91,286 fish produced and subsequently caught in a fishery). With this model, total hatchery production costs averaged over the number of landed hatchery fish decreased logarithmically from around $30 (in 1993 dollars) per hatchery fish landed if only 2% of the released striped mullet are caught in the fishery, to $12 if 5% are caught, $6 if 10% are caught, $3 if 20% are caught, $1.20 if 50% are caught, and $0.60 if 100% are caught.

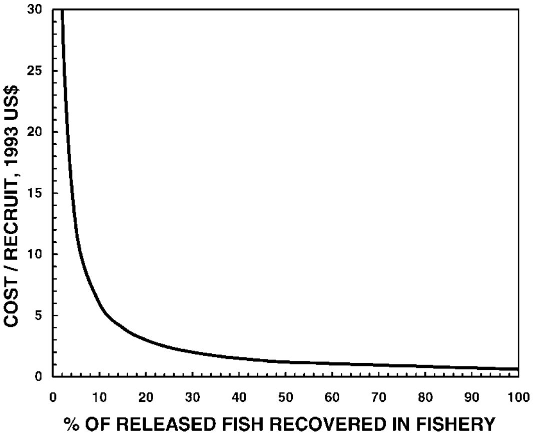

FIGURE 2.—Unit production costs apportioned over simulated hatchery striped mullet landings. Production cost per hatchery recruit in the fishery is for 85–110-mm TL fingerlings produced at the Oceanic Institute hatchery, Hawaii, and released into the wild in Hawaii. Cost-per-recruit estimates are based on total production costs to produce 91,286 fingerlings in the 85–110-mm size interval in 1993 (see Table 1) divided by the simulated amount of those hatchery fish in the fishery.

Discussion

Optimizing SAR Cost-Effectiveness

Since the early 1990s, there has been increasing awareness among marine ecologists of the critical relationship between the survival of cultured fish in the wild and release variables (such as SAR, release habitat, and timing of releases; e.g., Tsukamoto et al. 1989; Svåsand and Kristiansen 1990; Yamashita et al. 1994). Although the effect of SAR on performance of released hatchery fish was documented with coho salmon *Oncorhynchus kisutch* three decades ago (Hager and Noble 1976; Bilton et al. 1982) and has recently been put into theoretical perspective for summer flounder *Paralichthys dentatus* (Kellison and Eggleston 2004), the lessons first learned with salmon have not yet been totally embraced by stakeholders of marine stocking programs. An example of this is the difficulty encountered in Florida, where agency consideration of stocking fewer, but larger, red drum juveniles was not well received by anglers (e.g., Wickstrom 1993). Anglers judged the effectiveness of the enhancement program in Florida based on the numbers of fish released. Clearly, a much larger number could be stocked if the fish were released as postlarvae, given the mortality that occurs during grow out to larger juvenile sizes (Serafy et al. 1999).

Stakeholders in Florida have had little patience for ideas (such as those by Serafy et al. 1999) about improving cost–yield values by growing fish to larger sizes before stocking. Angler satisfaction appears to be intuitively tied to the magnitude of fish stocked. However, stewards of marine enhancement are now examining some of the basic, untested assumptions made about SAR. A search of the scientific literature shows that there is usually a direct relationship between recapture rate and SAR. Our results (this paper) reveal that releasing larger fish can result in greater cost-effectiveness if the increase in yield (because of the increase in survival afforded by releasing larger fish) more than offsets the increase in production cost of rearing larger fish. We need to look beyond our intuition in planning enhancement strategies and tactics. The Florida Fish and Wildlife Conservation Commission (FWC) provides a good example, as the agency's marine stock enhancement program has changed its policy of releasing only the less-expensive, smaller fish (~45 mm TL). The Florida FWC's current policy is first to conduct empirical studies to evaluate the most cost-effective SAR, and then to use that data to select SAR (Bill Halstead, Florida FWC hatchery manager, personal communication; Florida FWC strategic plan for stock enhancement, unpublished data).

The effectiveness of chosen release strategies has rarely been challenged by managers of marine stocking programs. We submit that under certain (but not all) circumstances (for example, stocking striped mullet into Kaneohe Bay when these data were collected), it is more cost effective to hold small fish in production longer and stock relatively large fingerlings than to stock small fish. There was clearly a strong relationship between cultured striped mullet SAR and survival after pilot releases in Hawaii (Leber 1995; Leber and Arce 1996). Until now, though, it has not been clear whether large fingerlings could be more cost-effective to stock than smaller fingerlings in Hawaii. Our CE(S) values provide that insight by linking performance (relative survival) in the wild to hatchery costs. The factors that affect CE(S) are the unit cost to produce fish and the yield per stocked recruit within SAR intervals. In effect, although the production cost of stocked 45–60-mm striped mullet was only two-thirds of the production cost of 85–110-mm fish, the former showed less than two-thirds the impact of the latter in the fishery. Indeed, based on this data set, fishery recovery rates for the 45–60-mm fish were, at best, less than a third of the recovery rates exhibited by the 85–100-mm fish. Modeling these data for all stocked size intervals showed that cost-effectiveness was greatest for the 85–110-mm SAR interval.

Our analysis reveals that, for Kaneohe Bay in the mid-1990s, stocking afforded a greater fishery contribution per dollar spent on production when intermediate-size, not small, striped mullet fingerlings were stocked. We must take care, though, not to generalize this result beyond the scope of our study. Our results do not suggest that large fingerlings should always be stocked by stocking programs; the point is that we should identify the most cost-effective size to stock. The optimal SAR may be small fish in some systems and larger fish in others.

Production Cost per Recruit

Factoring the known cost per fish produced by the proportion of the total number produced that are subsequently caught in a fishery provides a convenient way to examine production cost per yield (i.e., production costs expressed per hatchery fish landed in the fishery instead of per hatchery fish released). What proportion of the number of fish stocked into Kaneohe Bay would need to be recovered to offset hatchery production costs? In 1993, dockside landings sold for approximately $3 per pound. The hatchery fish landed had an average weight of about 0.5 kg (~1 lb; computed from data in Leber and Arce 1996). The production costs required to culture 91,286 fish in the optimal SAR interval averaged $0.60 per fish. Based on our knowledge of the optimal SAR in Kaneohe Bay, the cost to produce striped mullet in that SAR interval, and dockside price, we estimated (Figure 2) that if 20% of (91,286) stocked fish had been landed in the fishery at the time of this study, the hatchery costs to produce all of the fish stocked would have equaled the dockside price for those landed hatchery fish (i.e., total production cost divided by 20% of 91,286 fish stocked = ~$3 per fish). By the same token, if greater than 20% of the hatchery fish had been caught, dockside price would have exceeded total production costs averaged across those fish landed in the fishery. Only the fish production cost portion of the total cost of enhancement is considered here, as one example of how to compare cost and yield once the optimal SAR is known. All costs of enhancement could also be expressed this way (per hatchery fish landed) if those costs are known.

This simple model is one indicator that could be used in an economic evaluation of the effectiveness of a stocking program. If we factor in the costs of the fishery and other costs of stocking, which are beyond the scope of this paper, greater landings of hatchery fish would be needed to offset those costs. Costs of stocking should be compared with the value of fisheries (Hilborn 1998), and the rationale used to generate Figure 2 affords a simple approach to include in such comparisons.

Actual survival of the striped mullet stocked by Leber and Arce (1996) is unknown (only relative survival is revealed by the data on single capture histories obtained from coded wire tags). Total catch estimates of hatchery striped mullet in the Kaneohe Bay fishery would shed much light on the cost-effectiveness of stocking this species. Factoring total catch by the known percent contribution of hatchery fish in the catch (13% in 1994: Leber and Arce 1996) would reveal the total catch of hatchery fish and would enable comparison with the number of stocked fish required in the catch to break even on the costs of enhancement. Although total catch estimates were not available for the Kaneohe Bay striped mullet fishery, this is clearly a crucial statistic to consider in future studies of stock enhancement potential.

Would Releasing Millions of Postlarvae Be More Cost-Effective?

This study provides empirical support for Yamashita et al.'s (1994) and Kellison and Eggleston's (2004) calls for quantitative tests of the cost-effectiveness of stocking strategies. A weakness in our study was the lower limit of 45 mm TL chosen for our pilot releases (45 mm was the smallest size that had good coded wire tag retention [>90%, Leber et al. 1997]). What about releasing fairly easily produced and much larger numbers of smaller individuals (postlarvae or postmetamorphic juveniles)? This issue needs greater evaluation than it has received in the scientific literature, especially now that microsatellite DNA technology can be used to identify experimental treatment groups of fish that are too small to be tagged with conventional marks (e.g., Bert et al. 2003).

Current marine fish production technology in Hawaii evolved around intensive aquaculture systems rather than pond-based extensive production like that used for producing red drum in Florida, South Carolina, and Texas. Because extensive production techniques eliminate the cost of live-feeds production (rotifers and *Artemia* spp.), a major reduction in production cost is realized with extensive pond rearing compared to costs of intensive tank rearing of striped mullet in Hawaii. This is especially true if pond-reared postlarvae are harvested at a size small enough (e.g., ''fry'' ~ 30 mm TL) to eliminate the need for commercial feeds (e.g., McEachron et al. 1998; Bert et al. 2003; Smith et al. 2004).

By coupling good survival in the wild with the lower costs of extensive postlarvae production, releases of postlarvae may be cost-effective. However, there has been little development of ways to promote good postrelease survival of postlarvae and hardly any empirical evaluation of whether postlarvae constitute an economical SAR for the stocking of marine fishes (but see Smith et al. 2004). The approach presented in this paper needs to be broadened to include an empirical comparison of postlarval CE(S) with the CE(S) values for larger fingerlings. For striped mullet in Kaneohe Bay, cost-effective postlarval stocking would require lower CE(S) values than those attained from stocking larger (85–110 mm) individuals. The general key to making postlarval releases an efficient stocking strategy is a mechanism for achieving survival of released postlarvae that is high enough to compensate for intense predation. In contrast, the intensity of predation is relatively relaxed for larger individuals, owing in part to size-escape from predation.

It should not be surprising that there is a paucity of the data needed to assess the contribution of released postlarvae to fishery yields. This is largely because the marking technology used to identify postlarvae is relatively new. Although cultured postlarvae, once released, are much more difficult to identify as hatchery fish than are larger individuals that can be tagged with coded wire tags or visible tags, presently postlarval fishes can finally be marked. For example, using a tetracycline mark, Smith et al. (2004) tracked postlarval red drum into local fisheries in South Carolina. Natural resource agencies in Florida and Texas are currently applying microsatellite DNA (fingerprinting) techniques to identify red drum offspring from parents with documented genetic backgrounds (Bert et al. 2003; D. Abrego, Texas Parks and Wildlife, personal communication). These new tools for identifying very small individuals (albeit without much information content) provide the technology needed to advance our understanding of stock enhancement potential. To generalize SAR effects on stock enhancement economics, research on several species in multiple habitats is needed to compare the CE(S) of stocked postlarval fishes with the CE(S) values for larger sizes based on equation (5) to define the optimal SAR.

Considerations for Cost–Benefit Analysis of Stock Enhancement

This study is not an attempt to identify the economic value of stocking; it is a key incremental step needed for choosing the most cost-effective release size in subsequent tests of stocking effects. Once optimal release strategies are identified, it becomes more feasible to evaluate the full potential of stock enhancement, including economic effectiveness. The economic value of using stock enhancement to help replenish marine fish populations will depend on a suite of variables beyond the cost-effectiveness of release size. For example, uncertainties that can affect cost–benefit include the amount of fishing effort, release magnitude and production costs, survival of released fish to reproductive size and to the size exploited in the fishery, the value of recovered fish, consumer surplus value, competitive displacement effects of released fish, and the numerical contribution of released fish to subsequent generations of offspring. Most of the cultured striped mullet recovered in the fishery in Kaneohe Bay were within the size range of mature adults, and several were identified as ripe females or males with visible milt (Leber and Arce 1996). Siblings of those released hatchery fish will probably contribute offspring to subsequent year-classes in the wild. Hence, to fully evaluate value, some measure of all of the above variables, including the amount and benefit of increased reproductive potential and next-generation juvenile recruitment potential is also needed.

The understanding gained from this field study about the relative costs to put stocked fish into a fishery is a critical step for gauging the economic effectiveness of stocking strategies used to increase fish population size. However, a note of caution is required here. Clearly, more field studies are needed to identify how release strategies affect economic performance of stocking programs. As Leber et al. (1997, 1998) have pointed out, SAR effects on recapture rate can vary significantly with release season and release habitat. Thus, it may not be sufficient to identify the economically optimal stocking size for one location, season, or year in stock enhancement programs and then expect those results to be transferable to other locations, seasons, and decades. We have not yet achieved a generalized model for predicting optimal SAR outside of our study parameters.

Acknowledgments

We thank the Oceanic Institute's finfish program, and especially Cheng-Sheng Lee, Chris Kelley, Paul Bass, Garrett Miyamoto, Virginia Moriwake, Aaron Moriwake, Tony Ostrowski, and Chris Demarke, for their help in updating the published information on the various striped mullet production parameters used in the cost model. This project was 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 sub-agencies.

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