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[Article]

Aquaculture of the Atlantic Red Porgy

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Abstract.—Aquaculture of red porgy *Pagrus pagrus* (Sparidae) in North America was assessed by the investigation of broodstock conditioning and egg production, larval growth and survivorship, and juvenile grow out. Red porgy broodstock were collected off the coast of North Carolina and held in an outdoor recirculating seawater tank under ambient photoperiod and offshore bottom temperatures. Red porgy broodstock ($n = 20$) produced up to 300,000 viable eggs/d during their natural spawning period between January and March 2005. Larval survival to 10 d posthatch (dph) was 75.0 ± 2.2% (mean ± SE). Survival declined markedly after 13 dph and was 2.4% by 35 dph, when 1,200 postmetamorphic-stage juveniles remained. Larvae reached 11.2 ± 1.12 mm and 29.3 ± 0.55 mg at 35 dph, and juveniles reached 55 mm total length (TL) at 90 dph. Juvenile grow-out trials in recirculating tanks resulted in red porgy reaching 195 ± 0.32 mm TL and 158 ± 0.14 g at 313 dph and a weight-specific growth rate of 6.8%. The results suggest a lower larval growth rate for western Atlantic red porgy compared with Mediterranean red porgy culture; however, juvenile growth rates were significantly higher than previously reported. Given the high market demand for reef fish species, the red porgy appears to be a good candidate for marine fish culture in North America.

The red porgy *Pagrus pagrus*, also known as sea bream, silver snapper, or pink snapper, is a valuable marine finfish in the family Sparidae, inhabiting the Mediterranean Sea, the eastern Atlantic (from the British Isles to Senegal), and the western Atlantic (from North Carolina to Mexico and from Venezuela to Argentina; Mihelakakis et al. 2001a). Red porgy can reach a length of 75 cm and a weight of 10 kg (Kolios et al. 1997) and are an important component of the snapper–grouper complex off the southeastern U.S. Atlantic coast, particularly North Carolina and South Carolina.

In the Mediterranean Sea, red porgy are found at depths ranging from 18 to 250 m (Labropoulou 1999), migrating from shallower depths during the summer into deeper depths for the winter and staying within the temperature range of 14.5–24.2°C (Kolios et al. 1997; Labropoulou 1999). Juveniles prefer shallow sandy areas with seagrass, while adults are more often found in deeper waters (Labropoulou 1999).

Throughout the red porgy's range, diet consists mainly of polychaetes and decapods (Manooch 1975; Labropoulou and Papdopoulou-Smith 1999). Red porgy are protogynous hermaphrodites, beginning life as females and then transforming into males (Kokokiris et al. 1999). The seasonal change in photoperiod between winter and spring stimulates gonadal maturation and spawning (Manooch 1976), usually between March and April off the southeastern U.S. coast (Vaughan and Prager 2002).

Over the last two decades, red porgy populations have declined severely off the southeastern U.S. coast (Vaughan and Prager 2002; SAFMC 2006). Total landings increased from 335 metric tons in 1972 to over 900 metric tons in 1982, then declined steadily to 30 metric tons in 2000 (SAFMC 2006). In the 1970s,

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mean weight of red porgy in commercial and recreational fisheries was approximately 1.06 kg but declined to 0.66 kg by the late 1990s (Potts and Manooch 2002). The South Atlantic Fishery Management Council has established stringent requirements for capture of red porgy along the southeastern U.S. coast (Vaughan and Prager 2002; SAFMC 2006).

Red porgy are congeners of the red sea bream *P. major*, one of the most valuable and widely cultivated marine finfish (Foscarini 1988; Fukusho 1991; Koshio 2002). In 1998, aquaculture production of red sea bream in Japan was 82,500 metric tons; 81 million juveniles were produced, of which 30 million were used for stock enhancement and 51 million were used for aquaculture (Koshio 2002). Due to declining natural populations, high market value, and suitability for intensive culture in tanks and cages, red porgy are considered a promising species for farming in the Mediterranean Sea (Kentouri et al. 1995; Kolios et al. 1997; Hernández-Cruz et al. 1999; Roo et al. 1999; Mihelakakis et al. 2001a, 2001b; Papandroulakis et al. 2004) and South America (Aristizábal and Suárez 2006). Studies to date indicate that aside from high early mortality related to swim bladder inflation (Mihelakakis et al. 2001b; Papandroulakis et al. 2004), the red porgy is a robust species when grown under hatchery conditions (Roo et al. 1999; Mihelakakis et al. 2001b; Papandroulakis et al. 2004; Aristizábal and Suárez 2006) and growth rates exceed that of the gilthead sea bream *Sparus aurata*, sharpsnout seabream *Diplodus puntazzo*, and European seabass *Dicentrarchus labrax* (Kentouri et al. 1995). Despite the recent increase in red porgy aquaculture research in the Mediterranean Sea and Asia, no published data are available on red porgy culture in North America.

This paper describes an attempt to culture red porgy in Beaufort and Wilmington, North Carolina. We report survivorship and growth estimates of larvae and juveniles, compare culture performance with that of Mediterranean red porgy, and discuss the outlook for red porgy culture in North America.

Methods

Broodstock conditioning and spawning.—During March 2004, 50 adult (~1 kg) red porgy were collected off the coast of North Carolina at a depth of approximately 30 m using rod and reel. Fish were transported (<4 h) in a live holding tank to aquaculture facilities at the Center for Coastal Fisheries and Habitat Research, National Ocean Service, National Oceanic and Atmospheric Administration, Beaufort. Fish were initially held in an indoor, 19,000-L, round recirculating tank. At 18 d after capture, 20 fish with a mean (±SE) total length (TL) of 306.0 ± 4.7 mm and a weight of 373 ± 20.0 g were selected as broodstock and moved to a 31,000-L outdoor tank (diameter = 6.0 m; depth = 1.0 m) with recirculating seawater (salinity = 31.90 ± 0.24‰) under ambient photoperiod. A shade cloth was used to reduce direct sunlight by 70%. Water was exchanged (15–20%) weekly using ambient water from the estuary, and water temperature was adjusted monthly to reflect North Carolina offshore bottom temperatures as described by Parker and Dixon (1998) at depths from 27 to 33 m (Figure 1). Broodstock were fed a mixed diet of squid and shrimp ad libitum for 5 d/week. During the spawning season, eggs were collected (within 48 h of spawning) by filtering surface water (60 L/min) from the spawning tank through a 505-μm Nitex mesh net located in an adjacent tank. Viable (floating) and nonviable (sinking) eggs were separated in a 2-L separatory funnel, and the volume of viable eggs was determined. For larval culture experiments, eggs were transported in a temperature-controlled plastic bag with seawater and supplemental oxygen to the University of North Carolina Wilmington (UNCW) Aquaculture Facility, Wrightsville Beach.

Larval rearing.—Between 28 January and 3 March 2005, survival and growth of larval red porgy from egg through the metamorphic stages were studied under pilot-scale hatchery conditions at the UNCW Aquaculture Facility. The larval rearing system consisted of three 155-L, black, cylindrical larval rearing tanks (diameter = 77.5 cm; depth = 40.0 cm). Each larval rearing tank was supplied with 1-μm-filtered, flow-through seawater at an exchange rate of 2.5 times/d. Illumination was provided by 100-W, high-output fluorescent bulbs supplying full-spectrum lighting to simulate natural light. Light intensity was maintained at a constant level (500 lx) at the water surface. Photoperiod and temperature were maintained at 18 h light : 6 h dark and 22°C, respectively.

Approximately 50,000 eggs with a diameter of 1.00 ± 0.05 mm (mean ±SE; $n = 19$) were incubated (~48 h at 19°C), and hatch rate was determined volumetrically. Larvae were stocked into the 155-L rearing tanks at a density of 107 fish/L. Water salinity and temperature were maintained at 34‰ and 19°C. Temperature was increased to 22°C by 2 d posthatch (dph). Aeration was supplied at approximately 150 mL/min through a single diffuser (4.0 × 1.3 ×1.3 cm) placed in the center of the tank. Salinity, dissolved oxygen, light intensity, pH, and airflow were measured daily in each rearing unit.

Feeding.—At 3 dph, small (S-type) rotifers *Brachionus rotundiformis* enriched with AlgaMac 2000 (Aquafauna Bio-Marine, Inc., Hawthorne, California) were added to each rearing tank at a density of 6

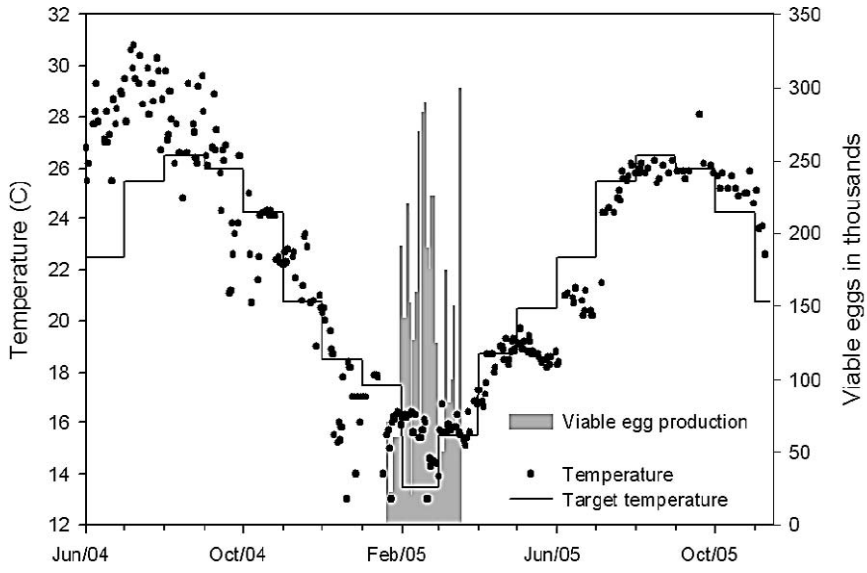

FIGURE 1.—Spawning duration and egg production of captive adult red porgy in relation to temperature in 2005. Temperature cycling simulated mean monthly bottom temperatures found at the 210 Rock south of Beaufort Inlet, North Carolina.

individuals/mL. Once feeding began, rotifer density was increased to 20 individuals/mL. Rotifer density was maintained by quantifying the rotifers in each culture vessel using volumetric methods and adding the appropriate number of enriched rotifers to make up the difference on a daily basis. Background algae *Nannochloropsis oculata* was added twice daily to maintain a density of 300,000 cells/mL. Larvae were co-fed artificial microdiets (crumble size from 250 μm to 3.0 mm; Nisshin Feed, Inc., Tokyo, Japan) beginning at 11 dph. At 12 dph, newly hatched nauplii of brine shrimp *Artemia* spp. (Argent Laboratories, Redmond, Washington) were introduced at 0.25 individuals/mL and rotifer feeding was reduced. At 17 dph, larvae were weaned onto enriched brine shrimp nauplii at a density of 1.2 individuals/mL and were subsequently weaned completely onto a dry diet by 26 dph.

Growth and survival.—To monitor growth, larvae were sampled volumetrically using a 1.27-cm polyvinyl chloride (PVC) sampling apparatus (PVC column equipped with a ball valve). Each tank was sampled at 3, 6, 10, 13, 20, 28, and 35 dph. Before sampling, aeration was increased to uniformly distribute larvae and vertical samples were collected ($n > 25$ larvae/sample). The larval density (larvae/L) was determined by dividing the number sampled by the volume of water collected. Larval survival on each sampling date was calculated as the quotient of larval density and stocking density, expressed as a percentage. Larvae were anesthetized (0.3 g/L solution of 2-phenoxyethanol in freshwater) and placed into a gridded 100- × 15-mm petri dish. Living larvae were distinguished from dead larvae by opacity and the presence or absence of a heartbeat.

Notochord lengths (NL; tip of snout to tip of notochord) were measured with an ocular micrometer. Wet and dry weights were recorded to the nearest 10 μg using a Sartorius electrobalance (Goettingen, Germany). Wet weights were recorded by weighing approximately 10 larvae on a microscope slide and then subtracting the weight of the slide. To determine dry weights, larvae were dried at 60°C for 72 h until they reached a constant weight.

Larval survival was measured volumetrically at 3, 6, 10, 13, 20, and 35 dph using the 1.27-cm PVC sampling apparatus. Before collecting vertical samples, tank aeration was increased to uniformly distribute larvae in the rearing tank. The larval density was determined volumetrically at 3 dph once larvae reached the first feeding stage. At 35 dph, larval survival was estimated by volumetric displacement.

Juvenile grow out.—At 36 dph, juveniles were transferred from the 155-L cylindrical larval rearing tanks to three flow-through raceways (216 × 52 × 20 cm = 160-L working volume). Fish were fed a commercially prepared finfish starter diet (Zeigler Brothers, Gardners, Pennsylvania) containing a protein : fat ratio of 55:15 through 91 dph. Growth was monitored by measuring TL and weight of at least 20 anesthetized fish per tank at 55, 75, and 90 dph.

TABLE 1.—Survival (mean ± SE) and growth of larval red porgy from hatch through metamorphic stages (35 d posthatch [dph]) during culture in 155-L tanks. Developing embryos were stocked at a density of 107 fish/L. Notochord length (NL) and wet weight are also expressed as mean ± SE.

	Survival		Growth	
Age (dph)	Larvae per liter	Percent	NL (mm)	Wet weight (mg)
3	60.1 ± 6.6	72.0 ± 8.2	3.2 ± 0.23	0.09 ± 0.07
6	60.1 ± 3.1	76.7 ± 3.9	3.3 ± 0.24	0.22 ± 0.05
10	60.1 ± 3.6	76.5 ± 4.6	3.8 ± 0.38	0.69 ± 0.12
13	31.8 ± 3.2	39.9 ± 4.0	4.5 ± 0.43	3.42 ± 0.32
20	15.7 ± 2.3	19.7 ± 2.9	6.5 ± 0.70	7.13 ± 0.40
35	2.5	2.4	11.2 ± 1.12	29.3 ± 0.55

Photoperiod, temperature, and salinity were maintained at 12 h light : 12 h dark, 22°C, and 34‰, respectively.

At 91 dph, 1,201 juveniles (3.79 ± 0.02 g) were transferred to an outdoor, 11.3-m^3, fiberglass recirculating tank (diameter = 4.57 m; depth = 1.2 m) with a working volume of 11,250 L and flow rate of 150 L/min. Fish were stocked at a density of 0.41 kg/m^3 and twice daily were hand fed a mixture of floating and slow-sinking commercially prepared finfish pellets (6.0–9.0 mm; Zeigler Brothers) characterized by a protein : fat ratio of 42:16.

Fish were reared under ambient photoperiod at 21°C and a salinity of 34 g/L through December 2005. Growth was monitored by measuring TL and weight of at least 100 anesthetized fish at 130, 172, 210, and 224 dph. Growth was expressed as daily weight gain ([final weight − initial weight]/time) and specific growth rate ($100 \times \{\log_e[\text{final weight}] - \log_e[\text{initial weight}]\}$/time), where time is in days.

Results

Broodstock Collection and Spawning

All red porgy experienced overinflated swim bladders as a result of the collection at depth. All swim bladders returned to normal within 24 h of capture, and collection mortality within 48 h was 3%. Spawning commenced naturally during the months of January, February, and March 2005, coinciding with water temperatures of approximately 13–15°C (Figure 1). During this natural winter spawning period in 2005, female broodstock produced up to 300,000 viable eggs/d (Figure 1). Peak spawning occurred in mid-February.

Larval Culture

A hatch rate (0 dph) of 75.0% produced a total of 37,500 yolk sac larvae. At 3 dph, larval density averaged 60.1 fish/L (Table 1). Larval survival remained constant through 10 dph, averaging 75.0 ± 2.2% (mean ± SE). Survival declined abruptly to 39.9 ± 4.0% by 13 dph and to 19.7 ± 2.9% by 20 dph. By 35 dph, survival decreased to 2.4%, and 1,200 postmetamorphic stage red porgy were produced. Larval NL and wet weight at 3 dph were 3.2 mm and 0.09 mg, respectively, increasing to 4.5 mm and 3.42 mg at 13 dph and 6.5 mm and 7.13 mg at 20 dph (Table 1). Observations suggest that most of the larval mortality after 13 dph resulted from overinflated swim bladders (Figure 2).

Juvenile Grow Out

On 55 dph, fish weight and TL averaged 0.58 g and 28.2 mm TL, respectively, increasing to 2.44 g and 48.6 mm TL by 75 dph. By 91 dph, juvenile red porgy averaged 3.79 g and 56.5 mm TL, the average daily weight gain was 0.08 g/d, and the specific growth rate was 8.7%/d (Table 2). Average fish weight and length were 32.0 g and 118 mm TL, respectively, by 172 dph and 51.8 g and 135 mm TL by 210 dph. At 313 dph, fish averaged 158 ± 0.14 g and 195 ± 0.32 mm TL, and the specific growth rate was 6.8%. Final individual weights ranged from 79 to 223 g. Feed consumption from 91 to 313 dph averaged 1.5% body weight/d, while overall feed conversion ratio ([dry weight fed]/[wet weight gained]) was 1.1. Survival remained high (94.2%) until 210 dph, when nitrogen saturation and high levels of ammonia were encountered due to mechanical problems with the recirculating system. By

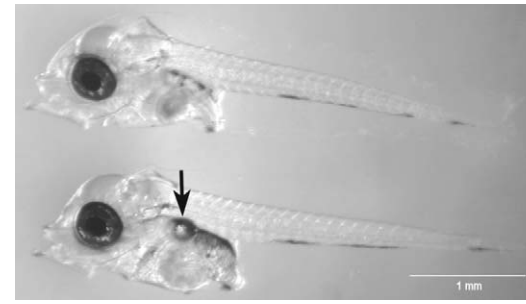

FIGURE 2.—Photograph of cultured red porgy larvae (at 10 d posthatch), depicting normal (top) and overinflated (bottom) swim bladders.

TABLE 2.—Growth and survival of cultured juvenile red porgy during pilot-scale grow out in three flow-through raceways (2.1 × 0.5 m) from 35 to 91 d posthatch (dph) and one 15.0-m^3 recirculating seawater tank (stocked with 1,201 juveniles) from 91 to 313 dph. Body weight and TL are expressed as mean ± SE.

Age (dph)	Body weight (g)	Average daily weight gain (g/d)	TL (cm)	Survival (%)
55	0.58 ± 0.01	0.03	28.2 ± 0.09	100
75	2.44 ± 0.05	0.09	48.6 ± 0.21	100
91	3.79 ± 0.02	0.08	56.5 ± 0.12	100
130	14.9 ± 0.55	0.28	90.9 ± 0.09	100
172	32.0 ± 0.56	0.41	118 ± 0.11	98.3
210	51.8 ± 0.72	0.52	135 ± 0.12	94.2
313	158 ± 0.14	1.03	195 ± 0.32	32.0

224 dph, survival decreased to 79.0%. To correct these problems, fish (224 dph) were temporarily transferred out of the system while the recirculating system and filtration package were repaired. Survival after transfer decreased to 65.3%, and final survival of juveniles from 90 to 313 dph was 32%.

Discussion

Artificial propagation of temperate and tropical reef fishes in North America, including gags *Mycteroperca microlepis* (Roberts and Schlieder 1983), red grouper *Epinephelus morio* (Colin et al. 1996), Nassau grouper *E. striatus* (Tucker et al. 1991; Tucker and Woodward 1996; Watanabe et al. 1996), black seabass *Centropristis striata* (Copeland et al. 2003; Watanabe et al. 2003), mutton snapper *Lutjanus analis*, yellowtail snapper *Ocyurus chrysurus*, and red snapper *L. campechanu*s (Watanabe et al. 2005), is challenged by controlled spawning in captivity, larval first feeding and survival through metamorphic stages, and temperature demands during grow-out phases. Based on results of this study, the potential for red porgy culture in North America appears optimistic.

Red porgy broodstock husbandry does present several challenges. Complications due to external parasites (*Cryptocaryon irritans*, *Amyloodinium ocellatus*, and monogeneans) were observed during adult husbandry but were resolved using traditional chemical treatment of copper sulfate, trichlorfon, or quinine hydrochloride (Noga 2000). Red porgy also have relatively small scales and thus require special handling by soft nets. As sparids capable of abrupt fast swimming, red porgy in captivity are easily startled, an event which usually results in fish jumping out of water and colliding with the side of the tank. Eye infections were highly prevalent in adult rearing systems, probably due to trauma induced by tank collisions. These observations suggest that tank culture of red porgy requires relatively large circular tanks or oval raceways designed to prevent collisions and mortality due to jumping.

The spawning of red porgy in captivity during this study was similar to that observed by Hernández-Cruz et al. (1999) and Mihelakakis et al. (2001a), demonstrating a tight correlation with winter photoperiod and temperature cycling. Red porgy egg production and viability are similar to reports by Mylonas et al. (2004). The results of our study demonstrated that large numbers of viable eggs (300,000 eggs/d) can be readily obtained during December through March from a broodstock population consisting of only 20 individuals. In addition, it is probable that the red porgy spawning season could be extended significantly using photothermal manipulation and out-of-season egg production, as are accomplished in other marine reef fishes (Howell et al. 2003).

Hatch rate (75%) was similar to the 70% rate reported by Radonić et al. (2005). Mean (±SE) egg diameter (1,000 ± 0.05 μm), however, was found to be larger than that reported by Manooch (1976; 800 μm), although red porgy in both studies were collected off the coast of North Carolina. When comparing egg diameters among other populations of red porgy, diameters measured in this study were similar to the 991–1,093 μm (Mihelakakis et al. 2001) and 990–1,070 μm (Mylonas et al. 2004) reported for Mediterranean fish. In contrast, Radonić et al. (2005; 900 ± 30 μm) and Machinandiarena et al. (2003; range = 830–930 μm) reported smaller egg diameters from Argentine broodstock. The direct cause of this difference in egg size is uncertain, as many factors (e.g., age, genetics, broodstock size, and broodstock conditioning; Bromage 1994) can affect egg diameter.

Growth performance of red porgy larvae during this study was slightly slower than that reported by Hernández-Cruz et al. (1999) and Mihelakakis et al. (2001a). Mihelakakis et al. (2001a) reported that larvae reached a mean TL of approximately 13 mm at 35 dph, whereas growth of our larvae at 35 dph was 11 mm NL. Assuming that NL differs by only a fraction of a millimeter from TL, significant differences in growth rates are apparent between these trials. Mihelakakis et

al. (2001a) used a larval rearing temperature nearly 2°C lower than that in our trials (19.5°C versus 22°C). It is unclear which rearing variables (e.g., stocking density, feeding regime, or photoperiod) or combination of rearing variables contributed to these differences in larval growth between these studies.

In this study, larval survival from 0 to 10 dph (75%) was significantly higher than that reported by Conides and Glamuzina (2001; 15%), who attributed high early mortality to first feeding difficulties and suggested that S-type and large (L-type) rotifers cannot be consumed by the larvae until 5 dph. Our results contradict this finding and suggest that S-type rotifers can be used effectively for first feeding. Furthermore, S-type rotifers were observed in the digestive tract of larval red porgy during this study as early as 3–4 dph, coinciding with full development of the mouth (Aristizábal 2005) and visual system (Roo et al. 1999) and timing of first exogenous feeding (Machinandiarena et al. 2003).

Mihelakakis et al. (2001a) reported that initial swim bladder inflation commences between 5 and 7 dph for Mediterranean red porgy. This timing was confirmed during this study; however, swim bladder overinflation was observed after 10 dph and contributed to significant mortality until 35 dph. The cause of swim bladder overinflation is unknown at present and may be caused by nutritional, developmental, pathogenic, or tank-induced reasons, such as inadequate circulation causing larvae to congregate at the tank surface. Interestingly, survival to the late larval stages during this study (2.5% at 35 dph) was lower than the survival (>10%) reported by Kolios et al. (1997) for this stage.

In contrast to larval growth, we observed juvenile growth to be significantly higher than previously reported. Kolios et al. (1997) reported that juveniles averaged 1.4 g by 80 dph and reached 360 ± 12 g within 19 months (with 6% mortality) in 250-m^3 wooden grow-out cages in the Mediterranean Sea. Our results indicate a much higher growth rate in raceway systems; juveniles averaged nearly 3.0 g by 80 dph and reached 158 g within 10.4 months. Although Kolios et al. (1997) did not report rearing conditions in the open-ocean cages, this comparison in growth rate indicates possible differences and the potential for optimizing red porgy growth in intensive systems under controlled environment conditions.

The observed larval and juvenile growth rates found in this study are confounding when compared with observations in the Mediterranean region. Comparisons of growth and survivorship between aquaculture operations are difficult given the inability to control for rearing and husbandry practices. It should also be noted, however, that large genetic differences do exist between Mediterranean and Atlantic red porgy (Ball et al. 2003, 2007) and may account in part for the observed growth differences.

In the Mediterranean Sea, the red porgy has been accepted as a viable candidate for finfish aquaculture due to its adaptability (Pavlidis et al. 2003) and fast growth (Maragoudaki et al. 2002; Papandroulakis et al. 2004). Some problems with unnatural coloration due to stress (Rotllant et al. 2003), background tank color (Van der Salm et al. 2004), and diet (Cejas et al. 2003) have been reported. In the present study, fish raised in black tanks and fed commercially prepared diets displayed primarily silver body coloration with pale redness in contrast to the vibrant red coloration seen in wild-caught fish. However, previous work by Cejas et al. (2003), Van der Salm et al. (2004), and Kalinowski et al. (2005) has demonstrated that natural carotenoids supplied by shrimp feeds and light background colors independently produce cultured fish with pigmentation similar to that of wild fish. These techniques warrant investigation, as red coloration is expected to be an important marketing advantage in the USA.

In summary, wild-caught adult red porgy broodstock readily adapted to captivity and responded to photothermal conditioning, spawning large numbers of viable eggs within their first year in captivity. Although larval rearing methods warrant improvement, routine marine finfish larval culture techniques were used successfully, resulting in high survival through 10 dph and significant numbers of juveniles by 35 dph. It is likely that survival can be significantly improved by solving the problem of swim bladder overinflation between 10 and 35 dph. Juvenile red porgy exhibited good growth, feed conversion, and survival in recirculating tanks. Given the high market demand for reef fishes, the current level of fishing pressure, and the subsequent population abundance status of the reef fishes, the red porgy appears to be an excellent candidate for commercial cultivation in North America. Since winter temperatures in North Carolina decline below 10°C, commercial grow out of the red porgy may demand the use of offshore cages or net pens south of Cape Hatteras, North Carolina, or the use of land-based recirculating systems in which optimum growing conditions can be maintained throughout the year. Future research is warranted in the areas of larval survival and juvenile grow-out methods and to gain a better understanding of production economics and marketability.

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