4-2004

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Eric T. Volkman

Christopher C. Kohler
Southern Illinois University Carbondale

Susan T. Kohler

Published in *North American Journal of Aquaculture*, Vol. 66, Issue 2 (April 2004) at doi: 10.1577/A03-046.1

Recommended Citation
Volkman, Eric T., Kohler, Christopher C. and Kohler, Susan T. "Assessment of Floating Vertical Raceways for the Culture of Phase-II Hybrid Striped Bass." (Apr 2004).

North American Journal of Aquaculture 66:125–132, 2004

Assessment of Floating Vertical Raceways for the Culture of Phase-II Hybrid Striped Bass

ERIC T. VOLKMAN,[1] CHRISTOPHER C. KOHLER,* AND SUSAN T. KOHLER

Fisheries and Illinois Aquaculture Center and Department of Zoology,
Southern Illinois University–Carbondale, Carbondale,
Illinois 62901-6511, USA

Abstract.—A floating vertical raceway is a system designed to provide a constant, unidirectional flow of water to fish confined in a flexible raceway that is suspended vertically in the water column. This study evaluated the potential of floating vertical raceways for the culture of phase-II sunshine bass (female white bass *Morone chrysops* × male striped bass *M. saxatilis*) reared at two densities (125 and 188 fish/m^3). Fish with a mean starting weight of 0.7 g were fed a diet containing 40% crude protein to satiation for 121 d. Fish in the low-density treatment reached a significantly higher final mean weight (160.0 g) than those in the high-density treatment (136.9 g). Survival was also significantly higher in the low-density treatment (81.1%) than in the high-density treatment (73.8%). No significant differences in water quality were detected for dissolved oxygen, total ammonia, un-ionized ammonia, or temperature between high-density and low-density treatments. Unlike the surrounding reservoir, water temperature inside the raceways remained destratified throughout the growing period. Based on the performance of fish, the high water quality maintained inside the enclosures, and ease of use, the floating vertical raceway system offers considerable promise as an alternative rearing system for deepwater impoundments.

Although the majority of freshwater finfish aquaculture in the United States is conducted in earthen ponds, many other bodies of water (e.g., flooded rock quarries and surface coal mine lakes) offer considerable potential and may be suitable for finfish production, provided efficient rearing protocols can be developed. These lakes could provide new and established fish farmers a previously underutilized resource for aquaculture. Both flooded quarries and surface coal mine lakes are different from most naturally formed lakes in that they tend to be very steep sided and deep (generally 20–40 m); they have a large volume of water and relatively little surface area.

Cages are currently the primary means to raise fish in deepwater environments. To take advantage of the depth of these bodies of water, specialized deep cages have to be constructed. Building and using such cages is feasible, but harvest of fish, maintenance, and routine cleaning becomes increasingly difficult with greater size. Additionally, cages effectively confine fish to one depth, often coinciding with the depth where water quality is worst during the warmest months of the year.

A research and larval rearing system that can be oriented in the vertical plane, thereby taking advantage of depth and ensuring high water quality, is the mesocosm bag or ‘‘large ecosystem bag.’’ Used extensively in Scandinavian countries for larval rearing and early life history studies, these bags have proven successful with Atlantic cod *Gadus morhua* and European flounder *Platichthys flesus*, among other species (van der Meeran 1991; van der Meeren et al. 1994; van der Meeren and Naas 1997). Mesocosm bag systems are similarly used by the National Marine Fisheries Service (NMFS) in the state of Washington for the culture of Pacific halibut *Hippoglossus stenolepis* (K. Massey, NMFS, personal communication). Utilizing recirculated water, sand filters and ultraviolet sterilization; these bag systems are similar in many respects to indoor recirculating systems. Taking water directly from the environment and passing it through the bag creates a water flow-through system. Flow-through floating vertical raceways (FVRs) have been used in research since 1973 for rearing various salmonid species (Martin and Heard 1987). Compared with traditional rearing methods, FVRs have a number of positive attributes: (1) lower construction and maintenance costs than ponds, (2) more adaptability to sites that do not allow shore-based operations, and (3) higher water quality when compared to cages (Martin and Heard 1987). Despite these advantages, FVRs have not been previously evaluated for use with nonsalmonid freshwater finfish.

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* Corresponding author: ckohler@siu.edu

[1] Present address: Department of Forestry and Natural Resources, Purdue University, 195 Marsteller Street, West Lafayette, Indiana 47906, USA.

Received September 17, 2003; accepted December 30, 2003

An FVR is constructed of water-impervious material with only the top and bottom open to the environment. A means to suspend the raceway vertically in the water column and a method to inject water from outside the raceway into the top of the unit are also incorporated into the system. By placing the top of the raceway out of the water, a unidirectional flow of water out the bottom is ensured when new water is pumped into the top of the unit. Heard and Martin (1979) evaluated a variety of shapes and found the inverted frustum to be the most efficient. Because new water moves constantly through the system, oxygen depletion and metabolic waste buildup should not be a factor once an appropriate density of fish is found. By using an airlift system to introduce new water to the raceway, incoming water can be drawn from a range of depths ensuring that dissolved oxygen (DO) and temperature requirements are met.

In addition to a suitable culture system for steep-sided bodies of water, a suitable species to culture must be identified for each region. Because of great promise already shown for sunshine bass (female white bass *Morone chrysops* × male striped bass *M. saxatilis*) culture in southern Illinois (Kohler et al. 2001), this hybrid was chosen to evaluate the potential of FVRs for freshwater nonsalmonid aquaculture. The sunshine bass is more commonly cultured than the palmetto bass (female striped bass × male white bass) (Tomasso et al. 1999). Both artificially spawned hybrids show stereotypic hybrid vigor, growing faster to a larger size in the first 2 years of life (Kohler 2000; Rudacille and Kohler 2000). Suitable temperatures for the culture of these hybrid bass have been reported as 16–32°C with optimal growth occurring between 25°C and 30°C (Kohler 2000).

Culture of the hybrid striped bass entails three phases of development. From hatching to a total length (TL) of 25–63 mm is considered phase I (Brewer and Rees 1990); phase II occurs when fish are grown to 254 mm TL, taking 5–9 months; and phase III is grow-out to market size (about 680 g), generally occurring in the second year after hatching (Brewer and Rees 1990). Although growth up to 225–350 g is possible in the first growing season in indoor systems (Hodson 1989), growth to 110–120 g is the generally accepted goal for the first year of pond culture (Morris et al. 1999).

Our study was an attempt to determine whether FVRs could be effectively used as an alternative for cage culture of freshwater finfish in a temperate climate. Because there is no literature on FVRs in this role, two densities were selected, based on cage culture densities, as an initial attempt to establish an appropriate stocking rate for future FVR research.

Methods

Six fabric raceways coated with polyvinyl chloride (PVC) and having an inverted frustum design (Figure 1) were purchased from a commercial supplier (Ringger Foods, Aquaculture Division, Gridley, Illinois). The raceways were 4.87 m deep with a 1.83-m-diameter top; the bottom of the frustum tapered to a 1.21-m diameter, which had a 0.60-m-diameter drain hole in it. The water volume utilizable by fish was between 8 and 8.4 m^3, the actual volume of water available to fish varying with how far the raceway extended above the surface of the water. This distance was affected by changes in the buoyancy of the barrels used for floatation, which changed with temperature and personnel walking on the dock. Throughout the experiment, all calculations were based on an 8.0-m^3 volume. A metal grate (mesh size, ~1.9 cm) was riveted to the PVC-coated fabric and enclosed the bottom of the raceway to deter predators and scavengers from entering the raceway. Minnow seine net material (mesh size, ~4 mm) was sewn to the metal grates to prevent escape of experimental fish until they exceeded 5 cm TL and was removed thereafter.

The FVRs were floated from a dock constructed of treated lumber and decked with plywood. Metal and plastic 208-L barrels provided buoyancy for the dock. The dock system was rectangular and consisted of six square cells (5.9 m^2), one cell for each individual raceway. A 0.61-m-wide walkway formed the perimeter of the dock with a 0.61-m-wide walkway bisecting the rectangle lengthwise. Rope was used to secure each raceway to the dock by passing it through grommets at the top of the raceways and attaching it to eyebolts fastened to the dock. The dock was anchored from each corner to cinderblocks sunk in the reservoir. Although the dock remained generally in the same location, it could move up to 3 m in any direction depending on wind direction and speed.

A centralized airlift system provided water circulation to the individual raceways. To facilitate maximum water flow, a PVC shower drain fitting (~10 cm diameter) was secured to the outside of each raceway 2–3 cm above the water line (Parker and Suttle 1987). For each raceway, a hole was cut through the raceway fabric, using the shower fitting as a template, and a 10.1-cm PVC 90° elbow was attached to the shower fitting, the bottom of

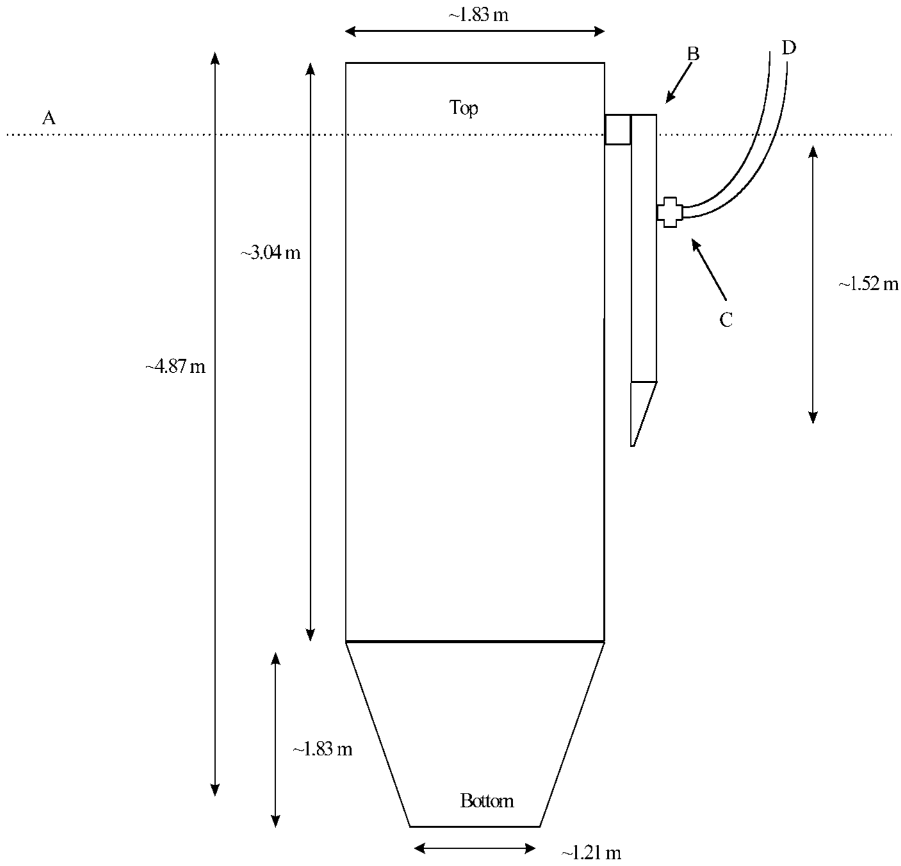

FIGURE 1.—Side-view schematic of the floating vertical raceway system and associated air lift system used to rear sunshine bass. Labeled structures are as follows: A = approximate water level, B = 10.1-cm polyvinyl chloride pipe (PVC) 90° elbow, C = 2.5-cm ball-and-joint PVC nozzle, D = 2.5-cm flexible plastic air hose.

each elbow being attached to a 1.5-m length of 10.1-cm PVC pipe, hereafter referred to as the lift tube. The bottoms of the lift tubes were cut at 45° angles to maximize water intake. Rigid plastic netting was placed over the ends of the lift tubes to stop unwanted fish from entering the raceway. Lead weights were tied to the bottom of the lift tubes to maintain a downward orientation when the system was operating.

Approximately 76 cm below the elbow, a 2.5-cm hole was drilled in the lift tubes to accommodate a ball-and-joint PVC nozzle attached to a flexible 2.5-cm plastic hose. The nozzles on the air delivery system attached to the lift tube were used for fine adjustments to water flow to ensure equal water flow to all raceways. The flexible plastic hose ran to the surface and was attached to an air manifold system of 5-cm PVC piping, which ran the length of the dock. Flexible 5-cm diameter potable water tubing was attached to the air manifold pipe and run to the shore about 50 m distant. The potable water tubing was then attached to a 1-hp regenerative air blower (Aquatic Ecosystems, Apopka, Florida) powered by a 220-V electrical outlet located on shore.

A 5-cm ball valve was attached to the PVC pipe running from the regenerative blower to allow venting of some or all of the compressed air to the atmosphere. Venting allowed maintenance to the regenerative blower without turning the system off and also a reduced water flow during the winter months to avoid potential super-cooling. An identical bypass valve was placed on the air manifold system on the dock and was used to turn off water flow during feedings to allow for observation of fish. Water flow through each of the raceways averaged 246 L/min.

Temperature and dissolved oxygen were measured daily at dawn with a YSI Model 55 oxygen meter (YSI, Inc., Dayton, Ohio) equipped with a thermister. Readings were taken at an anchored buoy approximately 10 m from the dock and in each of the six raceways. Data were collected at three depths within each raceway (the surface, 1 m, and 3 m below the surface). Measurements at the anchored buoy were taken at 4 depths (the surface, 2 m, 3 m, and the maximum depth [ranging from 5 to 7 m], which changed throughout the growing season due to rain and evaporative loss). All readings were completed within 1 h of daybreak. In addition to the daily temperature readings, two HOBO temperature data loggers (Onset Computer Corporation, Pocasset, Massachusetts) were programmed to record water temperature every hour for the course of the study. One temperature logger was placed 2 m below the surface of the water in a raceway. Another temperature data logger was suspended 2 m below a buoy anchored approximately 20 m from the raceway complex.

Ammonia, nitrite, and pH were measured each week of the study from water samples collected 2 m below the surface of each raceway with a Lamotte deepwater sampler (Lamotte Inc., Chestertown, Maryland). Additionally, a water sample was taken at the same depth at the anchored buoy 10 m from the dock. Water pH levels were analyzed with Hach Aquachek water quality test strips (Hach Company, Loveland, Colorado), and total ammonia and nitrite levels were measured with a Lamotte aquaculture pond test kit (Lamotte, Inc., Chestertown, Maryland). The percentage of total ammonia as un-ionized ammonia was calculated from pH and water temperatures following Piper et al. (1989).

Sunshine bass were obtained from Keo Fish Farm, Keo, Arkansas, and transported in a hauling tank with supplemental oxygenation to the reservoir at the Experimental Pond Demonstration Center, Southern Illinois University, Carbondale. The fish had a mean weight of 0.7 g and a mean total length of 30 mm. After a numeric count, the fish were placed in buckets and boated to the dock system. One of two density treatments was randomly assigned to each raceway so that three raceways were stocked with 1,000 fish (125 fish/m^3) and the other three raceways with 1,500 fish (188 fish/m^3). Initial treatment densities corresponded with 0.09 kg/m^3 and 0.13 kg/m^3.

The fish were fed to satiation twice a day throughout the growing season (121 d) with a 40% crude protein diet (Nelson and Sons Silver Cup, Murray, Utah). Satiation was considered the point at which little or no feeding response occurred as food was distributed into the raceways. The amount of food provided each raceway was recorded daily. Subsamples of fish were taken every 4 weeks throughout the growing season to measure total length (nearest 1.0 mm) and weight (nearest 0.5 g). Subsampling was accomplished by cast-netting 15 fish from a raceway and transferring them with a dip net to a cooler filled with water treated with 25 mg/L MS-222 (tricaine methanesulfonate). After anesthetizing, sampled individuals were removed separately from the cooler, and total lengths and weights recorded. Once measured, the fish were allowed to recover before being returned to their respective raceways. This procedure was repeated for each of the six raceways. At the conclusion of the growing season, a numeric count of all surviving fish was conducted. Of the fish initially stocked into each raceway, 10% were measured for total length and weight using the same protocol as the monthly measurements.

Performance of the experimental treatments was evaluated using several production criteria. Feed conversion ratio (FCR), survival rate, mean daily growth rate, and standing crop at harvest were all measured. Additionally, specific growth rate (see Hopkins 1992) was calculated as specific growth rate = $[(\log_e W_f - \log_e W_i)/\Delta t]$ 100, where W_f is the final weight, W_i is the initial weight, and Δt is the period of feeding in days. Fulton's condition factor (K_{TL}) was simply weight/total length^3.

All statistical comparisons used a t-test at $\alpha = 0.05$. Weight distributions were analyzed for normality using a Shapirio–Wilk test for goodness of fit. Analyses were performed with JMPIN version 4.0.3, (SAS Institute 2000).

Results

Over the 121-d trial, sunshine bass grew from a mean starting weight of 0.7 ±0.31 g (mean ± SD) to 160.0 ± 41.5 g in the low-density treatment and to 136.9 ± 41.2 g in the high-density treatment (Table 1); the difference between treatments was significant. Growth (both in terms of weight and in terms of total length) was not significantly different between treatments. Fish in the low- and high-density treatments had average growth rates of 1.3 and 1.2 g/d, respectively, and specific growth rates of 4.5 and 4.4%/d. Fulton's condition factor was 1.59 for the low-density treatment and 1.56 for the high-density treatment; these values were not significantly different.

The food conversion ratios, 1.4 for the low-density treatment and 1.5 for the high-density treatment, were also not significantly different. Standing crop at harvest was not significantly dif-

TABLE 1.—Survival, growth, size, and feed conversion data (mean ± SD) for two densities of hybrid striped bass reared for 121 d in floating vertical raceways placed in an impoundment (about 7 m maximum depth) in southern Illinois. Final mean weight and final total lengths between treatments were compared with a repeated-measures design. Comparison between treatments for feed conversion ratio, survival, mean daily growth, specific growth rate, standing crop at harvest, and condition factor were accomplished with a *t*-test. All statistical analyses were performed at α = 0.05. Significant differences are indicated by asterisks.

Stocking and harvest metrics	High-density (188 fish/m^3) raceways	Low-density (125 fish/m^3) raceways
Mean weight (g) at stocking	0.7 ± 0.31	0.7 ± 0.31
Mean length (mm) at stocking	30.0 ± 5.2	30.0 ± 5.2
Final mean weight (g)	136.9 ± 41.2	160.0 ± 41.5*
Final mean total length (mm)	206.1 ± 17.9	215.5 ± 17.8*
Feed conversion ratio	1.5 ± 0.1	1.4 ± 0.1
Survival (%)	73.8 ± 5.4	81.1 ± 5.9*
Mean daily growth rate (g/d)	1.2 ± 0.04	1.3 ± 0.003
Specific growth rate (%/d)	4.4 ± 0.03	4.5 ± 0
Standing crop at harvest (kg/m^3)	18.9 ± 1.5	16.2 ± 1.2
Fulton's condition factor[a]	1.59 ± 0.16	1.56 ± 0.27

[a] Weight/total length^3.

ferent between treatments and averaged 16.2 kg/m^3 for the low-density treatment and 18.9 kg/m^3 for the high-density treatment. There was a significant difference in survival between the low (81%) and high (74%) density treatments.

Water quality was not significantly different between treatments in terms of dissolved oxygen, temperature, total ammonia, or un-ionized ammonia (Table 2). Additionally, there was no detectable difference in DO, pH, or temperature with depth in either treatment to a depth of 3 m. Water quality characteristics inside the raceways were similar to those of the surrounding reservoir (Table 2).

Unlike the water outside the enclosures, the water inside the raceways was thermally destratified. During the 111-d period of the 121-d study when HOBO temperature data were available, the maximum daily temperature inside the raceways remained within the optimal range (25–30°C) on 71 d compared with 62 d outside the raceways (Figure 2). For 17 d, the maximum temperature inside the raceways was 30°C or greater, the highest temperature recorded being 32°C. In contrast, water temperature outside the raceways was 30°C or higher for 30 d and reached 33°C on 5 d. With respect to temperature below the optimal range, the maximum daily temperature was below optimal on 23 d inside the raceways compared with 19 d outside the raceways; both inside and outside the raceways, the lowest daily temperature recorded was 18°C.

Discussion

The floating vertical raceways proved to be highly suitable for rearing phase-II sunshine bass in a temperate reservoir. The phase-II sunshine bass reared in this study outperformed sunshine bass previously reared in earthen ponds at an adjacent site (Kohler et al. 2001), both in terms of mean weights attained (160 ± 41.5 g for low densities, 136.9 ± 41.2 g for high densities, and 90.2 ± 15.2 g for the best pond treatment) and in terms of survival (81.1% for low densities, 73.8% for

TABLE 2.—Means ± SDs and ranges (in parentheses) for water quality characteristics measured in high-density (188-fish/m^3) and low-density (125 fish/m^3) floating vertical raceways and at a 10-m lateral distance outside the floating vertical raceway complex. Values shown for temperature, dissolved oxygen, and pH are the means of measurements taken at the surface and at 1-m and 3-m depths. Ammonia and nitrite measurements were taken from samples collected at the 2-m depth. High-density and low-density treatments were compared statistically by means of a *t*-test; none were significantly different (α = 0.05).

Characteristic	Outside	High density	Low density
Temperature (°C)	26.7 ± 3.3 (17.6–31.2)	26.8 ± 3.3 (17.6–31.0)	26.8 ± 3.3 (17.6–31.0)
Dissolved oxygen (mg/L)	5.9 ± 1.8 (0.9–9.46)	5.8 ± 1.8 (0.9–9.43)	5.9 ± 1.7 (0.9–9.43)
pH	7.3 ± 0.5 (6.8–8.4)	7.0 ± 0.6 (6.8–8.4)	7.3 ± 0.5 (6.8–8.4)
Total ammonia nitrogen (mg/L)	0.3 ± 0.4 (0–1.0)	0.09 ± 0.2 (0–0.7)	0.09 ± 0.2 (0–0.7)
Un-ionized ammonia nitrogen (mg/L)	0.07 ± 0.2 (0–0.49)	0.006 ± 0.01 (0–0.046)	0.005 ± 0.01 (0–0.046)
Nitrite-nitrogen (mg/L)	Below detection levels	Below detection levels	Below detection levels

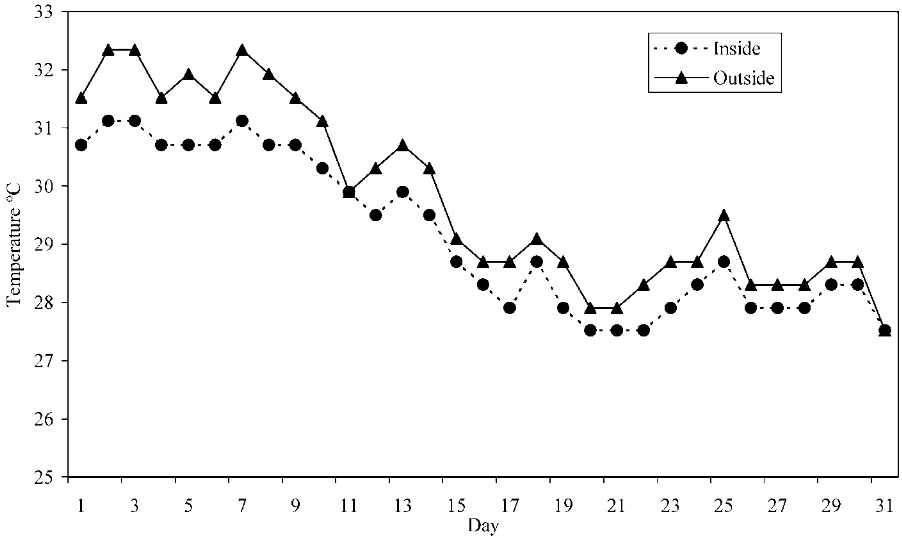

FIGURE 2.—Mean daily temperature at a depth of 2 m inside a floating vertical raceway used to rear sunshine bass and at a lateral distance of 20 m outside the rearing complex during August 2001.

high densities, and 72.3% for the best pond treatment). However, both studies yielded survival rates less than the 80–95% generally expected to occur in pond culture (Kerby 1993; Morris et al. 1999). Feed conversion ratios (1.4 for low densities and 1.5 high densities) were higher than Kohler et al. (2001) achieved (1.1–1.2), but were excellent nonetheless. Although growth rates for total length and weight were not different between treatments, the significant difference in total lengths and weights indicate that the growth curves were beginning to diverge.

Water quality at both densities in the floating vertical raceways generally remained within acceptable levels throughout the course of the study. The mean level of dissolved oxygen in both treatments exceeded the minimum standard (>4.0 mg/L; Kohler 2000) for sunshine bass, except during a 6-d period of impoundment-wide hypoxia when levels inside the raceways fell to about 1.0 mg/L. The hypoxia, however, occurred late in the growing season when fish feeding had already decreased substantially and no change in fish behavior or survival was observed as a consequence. Weekly measurements of ammonia at daybreak in both treatment densities were well below the recommended exposure limit of 1.0 mg/L (Kohler 2000).

The daily temperature means and ranges were identical between treatments, the temperature inside the raceways being consistently lower at a 2-m depth than the temperature at the same depth outside the raceways (Figure 2). Although growth of hybrid striped bass occurs between 16°C and 32°C, maximum growth occurs between 25°C and 30°C (Kohler 2000). The maximum daily temperature inside the raceway was in the optimal growth range on 64% of the experimental days versus 56% of study days outside the raceways. Although limited growth of hybrid striped bass can occur above 30°C, exposure to higher temperatures probably increases stress and vulnerability to disease outbreaks, in addition to reduced feeding. Therefore, the number of days when the fish were exposed to temperatures greater than 30°C is potentially critical. Fish in the raceways experienced these stressful temperatures on 15% of the trial days, whereas fish confined in cages at 2-m depth would have been exposed to thermal stress on 27% of the days during the growing season. Temperatures inside the raceways fell below the optimal range more often than the temperatures outside (21% of study days versus 17%).

The significant difference in final size between treatments is probably attributable to density-dependent biotic factors, as no significant differences were noted in abiotic factors (i.e., dissolved oxygen, un-ionized ammonia, and temperature). In two studies, Kemeh and Brown (2001) found no significant effect of density on the growth of phase-II sunshine bass reared in a water recirculating system with biomass ranging from 0.8 to 2.7 kg/m^3 (equivalent to 100–350 fish/m^3) and 2.5–15.0 kg/m^3 (equivalent to 150–725 fish/m^3), though growth rates were divergent. However, growth rates inverse to fish density have been noted in several species of fish, including, pumpkinseeds *Lepomis gibbosus* (Wang et al. 2000), Atlantic salmon *Salmo salar* (Soderberg et al. 1993), cutthroat trout *Oncorhynchus clarki* (Kinchi and Koby 1994), and rainbow trout *O. mykiss* (Piper et al. 1989; Holm et al. 1990).

Hybrids of striped bass and white bass are social fish and readily form schools once a critical number of individuals is reached. Schooling behavior may serve to stimulate feeding. In this study, sunshine bass formed schools immediately upon introduction to the FVRs in both density treatments (125 fish/m^3 and 188 fish/m^3). Schooling behavior in sunshine bass may be a function of density, absolute number, and enclosure shape: Kemeh and Brown (2001) noted no schooling below a density of 275 fish (5.0 kg/m^3) in rectangular tanks.

In the FVRs, dissolved oxygen levels remained constant with depth, whereas un-ionized ammonia levels rose shortly after feeding for up to 2 h and then fell sharply. The constant DO profile with depth and the lack of metabolic waste build up indicate that the carrying capacity of the FVRs had not been reached. If carrying capacity had been approached, it was expected that dissolved oxygen levels would have decreased with depth, as high DO water was entering the raceways from the top. Had DO depletion with depth or metabolic waste build up been noted, increasing water flow to the raceways would have increased carrying capacity. A comprehensive overview of airlift design and performance reviews was studied to examine the possibility of improving the efficiency of the system (Parker and Suttle 1987).

This study establishes the potential of FVRs as an efficient culture system for rearing young, freshwater finfish in deepwater environments. If sunshine bass can survive winter in the raceways and in the subsequent year grow at even the average rate of a pond-reared fish, a farmer using FVRs could expect market-size fish ($>$650 g) earlier in the second season, and produce larger fish. Alternatively, a farmer could use an FVR system to raise fish through phase II and then sell the early phase-III fish to other farmers for final grow-out. No single aquacultural system is a panacea; differing situations and requirements call for a range of methods to rear fish in the most efficient means possible. Further investigation is required to empirically determine the maximum carrying capacity of FVRs for hybrid striped bass and other culture species and to refine flow rates and feeding strategies to facilitate maintenance of water quality.

Acknowledgments

This publication is based, in part, upon research conducted by the senior author for the purpose of accommodating the Master of Science requirements in the Department of Zoology, Southern Illinois University Carbondale (SIUC). We thank Keo Fish Farm for providing the hybrid striped bass used in this study. We also thank P. Wills and R. Combs for their significant assistance during the building of the floating vertical raceway system and D. Walther for assistance with caring for the fish. Support for this project was provided through the SIUC Office of Economic and Regional Development through the Rural Economic and Alternative Agriculture Initiative project funded by the Illinois Council for Food and Agricultural Research. Additional funding was provided by the North Central Regional Aquaculture Center under grant 2001-38500-10369.

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