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Growth, Condition, and Size Distribution of Paddlefish, *Polyodon spathula*, Juveniles Reared in Ponds at Three Densities

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Abstract.—A study was conducted to determine the effect of increasing density on growth and size distribution of paddlefish, *Polyodon spathula*, juveniles reared in ponds. Feed-trained paddlefish of mean weight (±SE) 25.8 ± 1.1 g were randomly stocked into nine 0.02-ha ponds at 12,355, 18,533, and 24,710 paddlefish/ha, three replications per treatment. The fish were fed daily in excess of what they would eat for 97 d, beginning with a floating trout diet containing 45% protein and 16% lipid and then transferring to a floating catfish diet containing 32% protein and 4.5% lipid. Survival at harvest was not significantly different ($P > 0.05$) among treatments and averaged 90%. Mean final weights (±SD) for the low-, middle-, and high-density treatments were 205.2 ± 54.1, 174.8 ± 53.2, and 178.6 ± 51.4 g, respectively. Best-fit distributions centered on these means were lognormal. The low-density distribution was significantly different ($P < 0.05$) from the two higher densities, which were not significantly different from each other ($P > 0.05$). Paddlefish weight at the minimum target length of 35 cm was estimated to be 100 g by regression analysis. The probability of paddlefish reaching or exceeding 100 g was 90% for the low-density treatment. For the two higher densities, probabilities were 79 and 78%, respectively. Mean Fulton's condition factors (FCFs) (±SD) were 250 ± 19, 242 ± 4, and 256 ± 37 for the low-, middle-, and high-density treatments, respectively. The FCF for the middle-density treatment was significantly lower than for the low- and high-density treatments ($P < 0.05$), which were not significantly different from each other ($P > 0.05$). CV, feed conversion ratio, and relative growth were not significantly different ($P > 0.05$) among treatments and averaged 0.43, 1.50, and 5.45, respectively. Monoculture of paddlefish juveniles in ponds results in a hierarchic size structure when density is at least greater than 12,355 paddlefish/ha. The effect is enhanced with increasing density but becomes asymptotic as density approaches 18,533 paddlefish/ha. Feeding in excess does not ameliorate the effect.

Paddlefish, *Polyodon spathula*, is an ancient chondrostian species native to the large river systems of the central USA. It is a filter-feeding zooplanktivore with only one close relative, the piscivorous Chinese paddlefish, *Psephurus gladius*. The paddlefish is characterized by a long (up to 30% of total length [TL]) spatulate rostrum, spiral valve, and heterocercal caudal fin. The body is naked except for a few partially embedded ganoid scales on the sides of the caudal peduncle and under the opercular flaps along the gill openings. It is light gray to black dorsally, fading to white ventrally. The skeleton is mostly cartilaginous (Mims and Shelton 2005). The rostrum, cheeks, and opercular flaps are covered with electroreceptors, which serve collectively as a sensory antenna for detecting swarms of zooplankton (Wilkens et al. 1997). Paddlefish are known to grow rapidly (Adams 1942; Ruelle and Hudson 1977; Pasch et al. 1980). They are long lived (up to 30 y) and can achieve sizes greater than 90 kg and 200 cm TL (Mims and Shelton 2005). Paddlefish require certain environmental stimuli, such as flowing water, along with gravel or cobble substrate for natural spawning; however, methods for propagation and fingerling production have been developed (Mims and Shelton 2005; Onders et al. 2005).

Where permitted by state regulations, paddlefish stocks are fished as a source of black caviar. The price paid to commercial fisherman for salted paddlefish roe exceeded $US220/kg during the 2006 season. The USA is the world's largest consumer of caviar, which traditionally has come from countries surrounding the Caspian Sea region, including Russia and Iran (Boeckmann and Rebeiz-Nielsen 2000). However, these sources are in decline from overfishing and are increasingly regulated by international agreement. As a result, domestic sources such as paddlefish are experiencing increased demand. Wild paddlefish stocks cannot sustain increasing harvest rates (Boreman 1997), providing opportunities for aquaculture to meet demand.

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Successful implementation of paddlefish aquaculture will require increased production of juveniles for stocking. Therefore, reliable and repeatable production methods must be developed. Maximizing stocking density for intensive pond rearing of juveniles is an essential part of this process; however, the upper limit of stocking density has not been tested for effects on growth in ponds. A study by Gershanovich (1983) determined that increasing paddlefish stocking density in tanks resulted in a hierarchic structure, with growth of individuals determined by position in the hierarchy. In effect, larger individuals suppressed growth of smaller fish and size variability increased with increasing density. In this study, the effects of increasing stocking density on growth, condition, and size distribution of paddlefish reared in ponds were tested.

Materials and Methods

The experiment was conducted at the Aquaculture Research Center, Kentucky State University, Frankfort, Kentucky, USA. Feed-trained tank-reared paddlefish fingerlings of average weight (±SE) 25.8 ± 1.1 g were stocked into nine 0.02-ha ponds on June 28, 2006. The paddlefish were propagated according to Mims and Shelton (2005) in April 2006 from broodstock captured in the Ohio River near Louisville, Kentucky, USA. Three replicate ponds were randomly assigned to each of the three treatment densities (12,355, 18,533, and 24,710 paddlefish/ha). The ponds were covered with netting, and a 1.5-horsepower surface aerator was positioned in the center of each pond. Feeding was begun on the day of stocking. Initially, the paddlefish were fed a 1.6-mm floating trout pellet (Rangen EXT 450; Rangen, Inc., Buhl, ID, USA) (45% protein and 16% lipid) at 10% of body weight per day (BWD). The paddlefish were fed at 1530 h daily with aerators off to allow for surface feeding. The aerators were restarted after 4 h and operated continuously until the next feeding. After 2 wk, the paddlefish were sampled, and a 3.2-mm floating catfish pellet (Onders et al. 2005) was added to the ration (Rangen Production 32) at 25% catfish diet to 75% trout diet; however, the total ration was not changed.

Sampling was repeated on July 25, and the ration was adjusted to 6% BWD and 50% catfish diet to 50% trout diet. On August 1, the ratio was adjusted to 75% catfish diet to 25% trout diet without adjusting the total ration. After sampling on August 9, trout diet was eliminated from the ration without changing the total. The paddlefish were sampled on August 23 without changes to the total ration. On September 6, the ration was adjusted to 4% BWD after sampling, and this procedure was repeated on September 19. However, an adjustment to 3% BWD was made on September 21 because of increasing ammonia levels, and this ration was continued until harvest.

Total dissolved oxygen (DO) and temperature were measured at 0830 and 1530 h daily using a YSI Model 57 Meter (Yellow Springs Instruments, Yellow Springs, OH, USA). Total ammonia nitrogen (TAN), nitrite, and pH were measured twice weekly; TAN by the Nesslerization method and nitrite by the diazotization method per APHA (1998) as adapted for use with the HACH DR/2500 Spectrophotometer (HACH Co., Loveland, CO, USA). An Oakton Model 510 Meter (Oakton Instruments, Vernon Hills, IL, USA) was used to measure pH. Unionized ammonia concentration was estimated from TAN according to the method described by Boyd (1990). Sodium chloride was added to the ponds to maintain chloride concentration above 3 mg/L for protection from nitrite toxicity (Tucker et al. 1989). Chloride was measured by the mercuric nitrate method (APHA 1998). Ponds were aerated continuously except during feeding to prevent supersaturation of DO.

Harvest was conducted on October 1–3, 2006. Total yield (kg) and number of paddlefish harvested from each pond were recorded. Twenty percent of the population from each pond was randomly sampled and individually weighed and measured for TL. Fulton's condition factor (FCF) (Anderson and Gutreuter 1982) was calculated for each paddlefish sampled. Survival, mean final weight, CV, feed conversion ratio (FCR), and relative growth (RG) were calculated for each replicate pond.

Crystal Ball (2000) software was used to fit the data to a suitable probability distribution.

Goodness of fit was assessed by the Kolmogorov–Smirnov "*D*" statistic. Distributions for each treatment density were compared using the Kolmogorov–Smirnov test (Hollander and Wolf 1999). Regression analysis (ln (wt) = 1.59 + 0.09 (TL), adjusted $r^2 = 0.95$, $n = 669$, and $P < 0.05$) was used to estimate paddlefish weight at 35 cm TL (minimum target length). The areas under the respective probability distribution curves were used to determine the probability of paddlefish in each treatment exceeding target weight. Data for FCF were analyzed by the Kruskal–Wallis test (Rosner 1995). Survival, CV, FCR, and RG were analyzed by ANOVA. In all statistical analysis, the difference was considered to be significant when $P < 0.05$.

Results

Total harvest from all ponds was 3055 paddlefish for a total yield of 560 kg (3111 kg/ha). Survival was not significantly different among treatments ($P > 0.05$) and averaged 90%. For the low-density treatment, mean FCF (±SD) was 250 ± 19. Mean FCF for the middle-density treatment was 242 ± 4, and for the high density, mean FCF was 256 ± 37. The FCF for the middle-density treatment was significantly lower than for the low- and high-density treatments ($P < 0.05$), which were not significantly different from each other ($P > 0.05$). CV, FCR, and RG were not significantly different ($P > 0.05$) among treatments and averaged 0.43, 1.5, and 5.45, respectively (Table 1).

Mean final weights for the low-, middle-, and high-density treatments were (±SD) 205.2 ± 54.1, 174.8 ± 53.2, and 178.6 ± 51.4 g, respectively. Best-fit distributions centered on these means were lognormal (Fig. 1). The Kolmogorov–Smirnov "*D*" statistic was 0.043, which was significant ($P < 0.05$) ($n = 669$). The Kolmogorov–Smirnov test showed that the low-density (12,355 paddlefish/ha) distribution was significantly different ($P < 0.05$) from the two higher densities (18,533 and 24,710 paddlefish/ha), which were not different from each other ($P > 0.05$) (Table 2). Paddlefish weight at the minimum target length of 35 cm was estimated to be 100 g by the regression analysis. The probabilities of paddlefish reaching or exceeding 100 g were 90, 79, and 78% for the low-, middle-, and high-densities, respectively.

Morning DO was significantly different among treatments ($P < 0.05$), averaging 7.37, 6.95, and 7.18 mg/L for the low-, middle-, and high-density treatments, respectively. In the low-density treatment, morning DO ranged from 2.9 to 10.4 mg/L. Morning DO in the middle-density treatment ranged from 4.1 to 10.8 mg/L, and in the high-density treatment, morning DO ranged from 4.8 to 10.1 mg/L. Afternoon DO in the middle-density treatment was significantly different from the low- and high-density treatments ($P < 0.05$), which were not significantly different from each other ($P > 0.05$). In the low-density treatment, afternoon DO averaged 9.06 mg/L, ranging from 6.7 to 15.8 mg/L. Afternoon DO in the middle-density treatment averaged 9.45 mg/L and ranged from

TABLE 1. *Growth, survival, feed conversion, and condition of paddlefish juveniles stocked at 12,355, 18,533, and 24,710 fish/ha in 0.02-ha ponds.*[1]

Density (fish/ha)	Mean final weight (g)	RG[2]	CV[3]	Survival (%)	FCR[4]	FCF[5]
12,355	205.2 ± 54.1a	5.75 ± 0.9a	0.42 ± 0.03a	85.5 ± 10.6a	1.24 ± 0.13a	256 ± 37a
18,533	174.8 ± 53.2b	5.02 ± 1.2a	0.44 ± 0.08a	94.7 ± 4.6a	1.36 ± 0.47a	242 ± 4b
24,710	178.6 ± 51.4b	5.58 ± 3.7a	0.42 ± 0.07a	89.6 ± 13.5a	1.76 ± 0.87a	250 ± 19a

RG = relative growth; FCR = feed conversion ratio; FCF = Fulton's condition factor; TL = total length.

[1] Values are means (±SD) for three replications. Means in a column with differing letters are significantly different ($P < 0.05$).

[2] RG = (mean final weight − mean initial weight)/mean initial weight.

[3] CV = SD/mean of replicate final weights.

[4] FCR = total diet fed (kg)/total wet weight gain (kg).

[5] FCF = (individual final weight/TL^3) × 10^5.

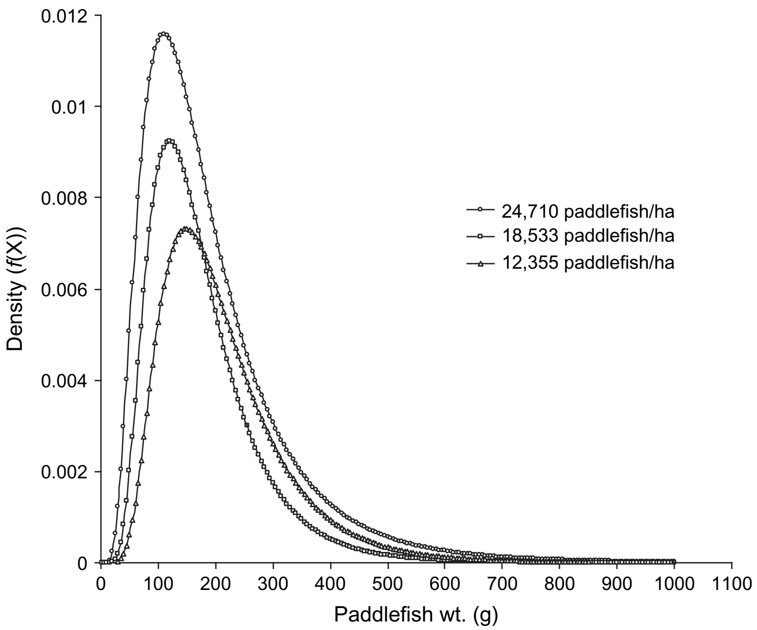

FIGURE 1. *Lognormal probability distributions for paddlefish stocked at three densities (12,355, 18,533, and 24,710 fish/ha) in 0.02-ha ponds:* $f(x,m,s) = \frac{1}{xs\sqrt{2\pi}} e^{-(\ln x - m)^2/2s^2}$, *where* m *and* s *are the mean and SD of the natural logarithm of individual paddlefish weights.*

5.7 to 15.6 mg/L. Finally, in the high-density treatment, afternoon DO averaged 8.97 mg/L, ranging from 5.1 to 19.9 mg/L.

Morning water temperature averaged 23.0 C in the low-density treatment and ranged from 14.4 to 29.9 C. In the middle-density treatment, morning water temperature averaged 23.6 C and ranged from 15.1 to 29.3 C, while in the high-density treatment, the morning water temperature averaged 22.8 C and ranged from 10.3 to 29.7 C. In the low-density treatment, afternoon water temperature averaged 24.8 C, ranging from 15.5 to 31.4 C, while afternoon water temperature in the middle-density treatment averaged 25.3 C and ranged from 15.1 to 31.9 C. Finally, in the high-density treatment, afternoon water temperature averaged 24.8 C, ranging from 11.6 to 31.9 C. The middle-density morning water temperature was significantly different from the low- and high-density treatments ($P < 0.05$), which were not significantly different from each other ($P > 0.05$). Afternoon water temperatures were significantly different among treatments ($P < 0.05$).

TABLE 2. *Kolmogorov–Smirnov test statistics and P values for comparison of the probability distributions of paddlefish juveniles stocked at 12,355, 18,533, and 24,710 fish/ha in 0.02-ha ponds.*

Density pairing (fish/ha)	Test statistic	*P* value
12,355–24,710	1.8	0.002
12,355–18,533	1.9	0.001
18,533–24,710	1.3	0.052

Nitrite levels in the low-, middle-, and high-density treatments were not significantly different from each other ($P > 0.05$) and averaged 0.04 mg/L. Maximum nitrite levels were 0.18, 0.29, and 0.26 mg/L for the low-, middle-, and high-density treatments, respectively. Unionized ammonia levels were also not significantly different among treatments ($P > 0.05$) and averaged 0.04 mg/L. Maximum recorded unionized ammonia levels were 0.2, 0.19, and 0.16 mg/L in the low-, middle-, and high-density treatments, respectively.

Discussion

In this study, monoculture of paddlefish juveniles produced size distributions that were not normally distributed and skewed toward smaller fish. CVs were high in each treatment density (Table 1), and the distributions showed an increasing effect when density was increased from 12,355 to 18,533 paddlefish/ha. However, no change was observed when density increased further to 24,710 paddlefish/ha. Gershanovich (1983) postulated that differential growth in groups of young paddlefish was the result of a hierarchic structure, which emerged from competition for "free space." Because paddlefish are ram ventilators, forward movement is continuous and essential to survival. As paddlefish density increases, the frequency of chance collisions also increases, with a concurrent decrease in free space. According to Gershanovich, these conditions increase energy expenditure of the paddlefish as a group and decrease feeding opportunities, enabling the hierarchic structure to emerge. Once this occurs, differential growth begins, and the variability in growth between larger and smaller individuals increases with time as larger fish inhibit the feeding activity of smaller fish. This hierarchic structure was also observed in the present study despite efforts to feed to satiation daily. In a study using mixed-size channel catfish, *Ictalurus punctatus*, it was reported that the smaller fish were not competitively disadvantaged by the larger fish during feeding activities (Unprasert et al. 1999). However, the effect of increasing density was not tested, and the fish were stocked together in distinct large and small size groups, so that no latent hierarchy could be observed.

Although there were some differences in FCF among treatments (Table 1), the differences were not density dependent, and they were similar to those reported in other studies. Mims and Knaub (1993) reported FCF for extensively (low density) reared paddlefish of similar age to those in the present study to be 242. Apparently, the paddlefish in all treatments were in good condition at harvest despite the variations in size. This effect was also reported in a density study of bluegill, *Lepomis machrochirus* (Anderson et al. 2002), where no significant differences in relative condition were reported among treatments despite decrease in weight gain (%) and increase in CV with increasing density. This result indicates that factors other than food availability contributed to differences in growth within treatments. Gershanovich (1983) pointed to genetic factors as the basis for the hierarchic structure. This possibility should be investigated for heritability in paddlefish occupying higher positions in the structure.

The effect of increasing density appears to be asymptotic between 12,355 and 18,533 fish/ha. No additional density effect was observed between 18,533 and 24,710 fish/ha. In addition to the similarity between probability distributions, the probabilities of exceeding target stocking weight were also similar at these densities. The results suggested that a threshold density effect, which as with the hierarchic structure, could not be overcome by satiation feeding. Konstantinov and Yakovchuk (1994) demonstrated that accumulated species-specific exometabolites (SSE) limited growth in monoculture of common carp, *Cyprinus carpio*, and grass carp, *Ctenopharyngodon idella*, with the effects increasing with increasing density. They also demonstrated that increased feeding could not reverse the effect and might enhance it. Although a threshold density was not observed in their study, it is feasible that SSE could increase to a growth-limiting threshold at a corresponding density threshold, resulting in the asymptotic growth effect observed in the present study. Therefore, the presence, chemical nature, and density effect of SSE in monoculture of paddlefish juveniles should be investigated.

In general, water quality was maintained within the parameters described by Mims and Shelton (2005). The statistical differences in DO and temperature were of no consequence as these parameters remained within acceptable limits throughout the study. Chloride has been shown to effectively block the uptake of nitrite through the gills of paddlefish (Boudreaux et al. 2007), as with the teleosts, and chloride was maintained at an adequate concentration during the study. The real effect of unionized ammonia on paddlefish juveniles is not known; however, none of the characteristic symptoms of ammonia toxicity (Boyd 1990) were observed.

A large number of paddlefish in each treatment actually reached target weight during the experiment (90% at 12,355 paddlefish/ha, 79% at 18,533 paddlefish/ha, and 78% at 24,710 paddlefish/ha). Paddlefish are capable of rapid growth. For example, in the present study, RG averaged 5.45 (Table 2) and ranged from 2.57 to 9.65 over the 97-d study period. Onders et al. (2005) reported RG of paddlefish juveniles (12,355 fish/ha) fed trout or catfish feeds for 97 d at 10.4 and 10.0, respectively. In addition, despite the high feeding rates used in this study, FCR was lower (Table 1) than the typical range (2:1–4:1) reported by Mims and Shelton (2005) indicating a high gain in wet weight. It may be possible to reduce density effects, such as those observed in the present study, by removing fast-growing individuals as they approach target size. This would also allow for compensatory growth in slower growing fish and reduce overall feed requirements for production. Another possibility would be to increase the number of daily feedings without increasing daily amount fed. Wang et al. (1998) found that frequent daily feedings ameliorated size variation in groups of hybrid sunfish (female green sunfish, *Lepomis cyanellus* × male bluegill) caused by social interaction and inherent differences in growth rate.

In conclusion, this study demonstrated that monoculture of paddlefish juveniles in ponds results in a hierarchic size structure, which shifts toward smaller individuals as density increases. The density effect becomes asymptotic between 12,355 and 18,533 paddlefish/ha. Satiation feeding does not ameliorate the density effects.

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