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Research Article

Rearing Density Impacts Juvenile Bluegill *Lepomis macrochirus* Growth in a Recirculating Aquaculture System

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Abstract

The effects of rearing density on large juvenile bluegill *Lepomis macrochirus* growth in recirculating aquaculture systems are relatively unknown. This 63-day study evaluated three initial densities: low (6 kg/m³), intermediate (12 kg/m³), and high (18 kg/m³). Final densities were low (8.1 kg/m³), intermediate (16.6 kg/m³), and high (20.9 kg/m³). At the end of the study, fish reared in the low-density tanks had a mean (SD) weight of 95.99 (7.49) g, which was significantly heavier than the 75.70 (4.28) g mean weight of fish in the high-density tanks. At 86.23 (7.63) g, the weight of individual fish in the intermediate-density treatment was not significantly different from either the low or high-density treatments. Specific growth rate was also significantly greater in the low-density treatment than in the high-density treatment. Individual fish total lengths were not significantly different among densities, with mean (SD) values of 155 (4) mm, 152 (4) mm, and 148 (2) mm for the low, intermediate, and high-density treatments, respectively. Similar to fish weight, condition factor was significantly greater in the low-density treatment than in the high-density treatment, while condition factor in the intermediate-density treatment did not differ significantly from the other treatments. Tank gain, percent gain, and feed conversion ratio did not differ significantly among treatments. These results indicate that of the three bluegill rearing densities evaluated in this study, the intermediate initial density of 12 kg/m³ appeared to produce the best balance of individual fish growth and total bio-

mass production.

Keywords:
bluegill; *Lepomis macrochirus*; rearing density; growth

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Introduction

Bluegill (*Lepomis macrochirus*) are a member of the Centrarchidae family native to the eastern and central United States [1]. They are a popular sport fish with recreational anglers, particularly with youth and inexperienced anglers. Bluegill are produced both extensively and intensively by fish hatcheries [2], [3], [4], [5], with catchable-sized bluegill used for put-and-take fisheries in urban settings [6], [7].

Although pond production remains important for bluegill culture, intensive culture is used to improve growth to more efficiently and effectively meet stocking timelines [7], [4]. Rearing bluegill to catchable sizes exceeding 15 cm total length has benefited from the controlled temperatures, optimized feeding, and enhanced growth achievable in Recirculating Aquaculture Systems (RAS) [4], [8], [9]. However, because bluegill rearing in RAS is a relatively recent development, considerable information regarding rearing parameters still needs to be determined.

Rearing density is a fundamental component of fish culture. In aquaculture rearing units, rearing density is the weight of fish per unit volume of the rearing tank [10]. While high rearing densities are frequently used to maximize fish production in limited rearing units [11], they can negatively influence both individual fish rearing performance and total biomass production [12], [8] by reducing dissolved oxygen and increasing carbon dioxide and nitrogenous wastes [13]. Growth, food conversion efficiency, and fin condition have all been shown to decrease at high rearing densities [14]. High densities can also lead to aggression, competition, and other negative social interactions, that can potentially lead to increased stress and disease susceptibility [15], [16]. High-density rearing can create selection pressure for higher activity levels and increase use of higher water velocity areas [17]. Lastly, the survival of hatchery-reared fish after stocking into natural environments can also be negatively affected by high rearing densities [18], [19], [20]. Although high rearing densities may

maximize total yield [4], [21], [22], for hatcheries producing catchable-sized bluegill, the size of individual fish at the time of release into recreational fishing waters is often prioritized over total yield.

Few studies have specifically examined rearing densities during the intensive rearing of bluegill and other small centrarchids. In a small laboratory-scale experiment, Anderson et al. [12] reported that bluegill weight, percent weight gain, condition factor, and feed efficiency were negatively related to rearing density. Treft et al. [5] reported a maximum rearing density for hybrid green sunfish (*Lepomis cyanellus*) reared in RAS of 30 kg/m³, but suggested higher densities could likely be used.

In the state of South Dakota, USA, catchable-sized bluegill are requested to be a minimum of 200 mm (total length) by fisheries managers for stocking. Because current hatchery rearing space is limited, South Dakota public fish hatcheries are challenged to meet the requested number of bluegill at this requested size. Thus, the objective of this study was to evaluate the effects of rearing density on bluegill growth and overall yield. This information is essential to guide hatchery management decisions that attempt to maximize catchable-sized bluegill production.

Materials and Methods

This 63-day experiment was conducted from 10 March to 12 May 2026 at Cleghorn Springs State Fish Hatchery, Rapid City, South Dakota, USA. Three initial stocking densities of juvenile bluegill were used: low (6 kg/m³; ~200 fish), intermediate (12 kg/m³; ~400 fish), and high (18 kg/m³; ~600 fish). These densities were chosen because of their historical use with bluegills during production rearing at the hatchery. Each density treatment was replicated in three 2,000-L tanks. At the start of the study, bluegill mean (SD) total length and weight were 131 (8) mm and 58.60 (14.78) g, respectively (N=200). The bluegill originated from pond production in 2025 and were reared in RAS for approximately seven months prior to use in this experiment. Bluegill as a group were placed into their respective tanks by weight to ensure that each tank for each treatment received exactly the same density in kg/m³. Thus, the number of fish per tank likely varied slightly. This experiment lasted for 63 days.

The trial used nine of 10, 1.83-meter diameter (2,000 L operational volume) fiberglass reinforced plastic dual-drain circular tanks (C.F. Maier Composites, Inc., Lamar, Colorado, USA) in a three-loop recirculating aquaculture system using a common sump. Water was supplied to all experimental tanks from the sump via a main loop. Before entering the tanks from this loop, the water was pumped through a GAIA UFB 300 ultrafine bubble generator (Gaia USA, Inc./Gaia Water Ltd., Mesa, Arizona, USA) for oxygenation. Effluent from the tanks passed through a ProfiDrum 65/60 drum filter (ProfiDrum, Rockley, Retford, Nottinghamshire, United Kingdom) for mechanical filtration before entering the sump. In addition to supplying water for the main loop, water from the sump was pumped to two other loops. One loop contained temperature control, ultraviolet sterilization, and carbon dioxide degassing. Temperature control was achieved with a Delta Hydronics 5-ton split unit (Delta Hydronics, Hudson, Florida, USA). Water sterilization was accomplished with a SITA 440-W UV lamp (S.I.T.A. Srl, Genoa, Italy), and carbon dioxide was degassed with an Oceans Design degassing tower (Oceans Design Inc., Colorado Springs, Colorado, USA). The other loop coming off of the sump was solely for nitrification with a self-contained moving bed bio-reactor (MBBR) containing 1.5 m³ of BioElement intermediate-density bio media (Integrated Aqua Systems, Escondido, California, USA). The MBBR was biologically mature throughout the study.

Water quality was managed according to target ranges throughout the trial, with no major deviations observed. Temperature and dissolved oxygen were measured daily in each tank using a Hach HQ2100 handheld meter (Hach Company, Loveland, Colorado, USA). Water samples for total ammonia nitrogen, alkalinity, and salinity were collected daily from main system effluent prior to treatment by the moving bed bioreactor and measured using a Hach DR3900 spectrophotometer (Hach Company, Loveland, Colorado, USA). Water temperature was initially 23.6°C, gradually increased to 28.3°C by day 7 and maintained at 28.3°C thereafter. Dissolved oxygen was maintained at or above 80% saturation, total ammonia nitrogen was maintained below 0.3 mg/L, alkalinity was maintained between 150 and 200 mg/L as CaCO₃, and salinity was maintained between 3 and 4 ppt.

Fish were fed 2.0-mm Bio-Oregon Bio-Vita (Bio-Oregon, Longview, Washington, USA) using Arvotec TD2000 automatic feeders (Arvo-Tec Oy, Huutokoski, Finland) to apparent satiation over a 12-h daily feeding period. Feed amounts were adjusted weekly. A 16-hour light:8-hour dark photoperiod was maintained throughout the trial. Mortalities were removed and recorded daily for each tank.

At the end of the experiment, 30 randomly-selected fish from each tank were weighed to the nearest 0.01 g and measured (total length) to the nearest mm. Final tank weights were measured to the nearest 5 g.

The following equations were used:

$$\text{Condition Factor (K)} = 100,000 \times W / L^3,$$

[where W is weight in grams and L is total length in millimeters [23]]

$$\text{Gain} = \text{final tank weight} - \text{initial tank weight}$$

$$\text{Gain (\%)} = [(\text{final tank weight} - \text{initial tank weight}) / \text{initial tank weight}] \times 100$$

$$\text{Feed conversion ratio (FCR)} = \text{food fed} / \text{gain}$$

$$\text{Specific Growth Rate (SGR)} = 100 * (\ln(\text{end weight}) - \ln(\text{start weight})) / (\text{number of days})$$

R version 4.5.2 was used for all statistical analysis with significance predetermined at $\alpha = 0.05$. Differences among treatments were tested using one-way ANOVA, with assumptions assessed before final model interpretation using Shapiro-Wilk and Anderson-Darling tests for residual normality and Levene's test for homogeneity of variance. Significant ANOVA results were followed by Tukey's HSD post-hoc testing. Feed conversion data was analyzed with a nonparametric Kruskal-Wallis test because ANOVA assumptions were not met. Tanks, not individual fish, were the experimental unit, so N=3 for all data.

Results

Mean final densities for the low, intermediate, and high-density treatments were 8.06, 16.57, and 20.85 kg/m³, respectively (Table 1). Final tank weights and final rearing densities differed significantly among all treatments. Tank gain, percent gain, and feed conversion ratio did not differ significantly among treatments.

Table 1. Mean ($\pm$ SD) final weight, gain, percent gain, feed conversion ratio (FCR) ¹, and final rearing density of tanks of bluegill reared at one of three densities for 63 days.

Means followed by different letters are significantly different ($P < 0.05$; $N = 3$).

	Initial Rearing Density			Statistics
	6 kg/m ³	12 kg/m ³	18 kg/m ³	
Start weight (kg)	11.98	23.96	35.94	
Final weight (kg)	16.12 $\pm$ 0.43 ^a	33.13 $\pm$ 4.16 ^b	41.71 $\pm$ 3.95 ^c	$F_{2,6} = 46.15$; $p < 0.001$
Gain (kg)	4.14 $\pm$ 0.43	9.17 $\pm$ 4.16	5.77 $\pm$ 3.95	$F_{2,6} = 1.79$; $p = 0.245$
Gain (%)	34.53 $\pm$ 3.55	38.28 $\pm$ 17.36	16.05 $\pm$ 10.99	$F_{2,6} = 2.93$; $p = 0.129$

Table 1 (continued)

	Initial Rearing Density			Statistics
	6 kg/m ³	12 kg/m ³	18 kg/m ³	
FCR ¹	3.59 ± 0.39	3.62 ± 1.35	14.73 ± 15.79	$\chi^2 = 5.42$; $p = 0.066$
Final rearing density (kg/m ³)	8.06 ± 0.21a	16.57 ± 2.08b	20.85 ± 1.98c	$F_{2,6} = 46.15$; $p < 0.001$

¹FCR = food fed/gain

Individual fish lengths did not differ significantly among densities (Table 2). Fish in the low-density treatment were significantly heavier and had higher condition factors and specific growth rates than fish in the high-density treatment. Mean weight, condition factor, and specific growth rate in the intermediate-density treatment did not differ significantly from either the low or high-density treatment. Only two mortalities were observed during the 63-day trial.

Table 2. Mean (± SD) final individual fish total length, weight, specific growth rate (SGR) ¹, and condition factor (K) ² of bluegill reared at one of three densities for 63 days.Means followed by different letters are significantly different ($P < 0.05$; $N = 3$).

	Initial Rearing Density			Statistics
	6 kg/m ³	12 kg/m ³	18 kg/m ³	
Length (mm)	155 ± 4	152 ± 4	148 ± 2	$F_{2,6} = 3.30$; $p = 0.108$
Weight (g)	95.99 ± 7.49a	86.23 ± 7.63ab	75.70 ± 4.28b	$F_{2,6} = 6.98$; $p = 0.027$
Condition Factor	2.47 ± 0.09a	2.40 ± 0.05ab	2.28 ± 0.03b	$F_{2,6} = 8.01$; $p = 0.020$
SGR ¹	0.78 ± 0.12a	0.61 ± 0.14ab	0.40 ± 0.09b	$F_{2,6} = 7.16$; $p = 0.026$

¹Specific Growth Rate (SGR) = 100 * (ln (end weight) – ln (start weight))/(number of days)²Condition Factor (K) = 10⁵ * (fish weight)/(fish length)³

Discussion

The results of this study, the first to evaluate bluegill rearing densities at a production scale, generally support findings from previous aquarium-based experiments with juvenile bluegill [12]. Anderson et al. [12] reported declines in final weight, percent weight gain, and feed efficiency with increasing rearing density. While these exact results were not replicated in the present study, a negative relationship between density and fish weight and condition factor was observed. The Anderson et al [12] study and this experiment differed substantially in fish size, density range, system scale, and production objective, with Anderson et al. [12] using smaller juvenile bluegills in indoor aquaria and this trial using larger fish in production-scale RAS. Therefore, the studies are best interpreted

as complementary evidence that bluegill growth can be density-sensitive across different intensive culture contexts [12], [4].

The densities evaluated in this experiment are difficult to compare to those used to effectively rear other fish species. For example, in hybrid green sunfish (bluegill x green sunfish cross) which are closely related to bluegill, Treft et al. [5] reported a maximum rearing density for rearing in RAS of 30 kg/m³, which is substantially greater than the highest density used in this experiment of nearly 21 kg/m³. Recommended maximum rearing densities in RAS for other fish species are highly variable, ranging from 18.75 kg/m³ for barramundi (*Lates calcarifer*; [24]), to 30 kg/m³ for cobia (*Rachycentron canadum*; [25]) and common carp (*Cyprinus carpio*; [26]), to 52 kg/m³ for turbot (*Scophthalmus maximus*; [27]), 120 kg/m³ for European eel (*Anguilla anguilla*; [28]), and 130 kg/m³ for Arctic char (*Salvelinus alpinus*; [29]).

Fish size may impact acceptable rearing densities, leading to the development of the density index [11]. This index calculates the mass of fish per unit of rearing space in proportion to individual fish length [11]. The highest density index obtained in this study was 0.22, which is well below the 0.50 limit recommended for striped bass (*Morone saxatilis*) and rainbow trout (*Oncorhynchus mykiss*) over 50-mm in total length [11]. The recommended density index for other salmonids in addition to rainbow trout are also much greater than those used in this study [30], [31], [32], [20], [33], [34].

Rearing density decisions during the hatchery production of centrarchids, such as bluegill, depends on the intended use of the product which will predicate the desired fish size [21], [22]. Because of limited rearing space, there is also frequently a trade-off between individual fish growth with total yield [4], [21], [22]. In South Dakota, catchable-sized bluegill are stocked into small urban ponds and family-oriented put-and-take fisheries to provide accessible angling opportunities [6]. A length of 200 mm at stocking is targeted because it corresponds to the preferred-length category in bluegill size-structure benchmarks [35]. This production trade-off is consistent with Li et al. [28], who identified stocking density as a primary determinant of RAS productivity and emphasized that appropriate density must balance production with fish growth, welfare, and health. In this study, bluegill lengths did not differ among the different densities, but individual fish weights were significantly heavier in the 6 kg/m³ group compared to the 18 kg/m³, with the intermediate 12 kg/m³ not significantly different than either of the other two treatments. However, the lowest density only had approximately 200 fish and a total ending weight (yield) of approximately 16 kg. The highest density (approximately 600 fish) produced the highest yield of nearly 42 kg of fish, although the individual fish on average weighed less. The yield from the intermediate density was 17 kg more than the low-density treatment and only 8 kg less than the high-density treatment. With no significant difference in the weight or length of the bluegill in the intermediate density treatment compared to the higher and lower densities, the intermediate rearing density used in this production-scale study likely provides the best balance between fish size and total yield of the three densities evaluated. It should also be noted that none of the densities used were able to produce the desired length of 200 mm. This indicates that factors other than density are likely influencing bluegill growth.

The results of this study, particularly the lack of a significant percent gain response, may reflect the 63-day trial duration and diet suitability. While the 63-day duration of this study exceeded the 53 days recommended by the National Research Council [36], Weatherup and McCracken [37] state that studies should run long enough for significant differences to occur. The feed used in this trial was 50% protein and 22% lipid, exceeding the previously recommended 40-to-42% protein and 10-to-12% lipid levels [12], [38], [39]. However, the potential interaction of diet with rearing density is unknown. Lastly, this study had only three replicates, which may have interfered with the ability to detect significant differences.

This study was conducted at a production-scale within a single recirculating aquaculture system. Thus, the results of this study are most directly applicable to similar hatchery grow out settings. Additional trials will be useful for refining density recommendations across production years, fish sizes, and grow-out durations. Stocking density should also be viewed as one component of a broader production roadmap. Experimentation on grading, temperature regimes, diets, feeding strategy, lighting,

environmental enrichment, and other aspects of rearing will all need to occur to enable the production of 200-mm bluegill within a one-year duration

Conclusion

The results of this 63-day study indicate that, of the three densities evaluated, an initial rearing density of 12 kg/m³ appears to provide the best balance between bluegill size and biomass yield. Additional research is needed to determine optimal rearing densities throughout the bluegill production cycle. In addition, research focusing on areas other than density is needed to achieve the desired bluegill length of 200 mm within the rearing durations used in this study.

Competing Interests

The authors have declared that no competing interests exist.

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