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ORIGINAL ARTICLE

Effect of natural food consumption on the first phase of pirarucu grow-out in ponds and cages

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ABSTRACT

Pirarucu, *Arapaima gigas* is a fish species of great social and economic importance in the Amazon region, where they are often farmed in earthen ponds. Intensive cage aquaculture has been growing in Brazil, which could be an alternative means to farm pirarucu, reducing costs and increasing productivity. We evaluated the contribution of natural food organisms in semi-intensive (ponds) and intensive (cages) production systems, and their effect on pirarucu growth and economic performance during the first phase of grow-out. Four ponds (300 m^2) and four cages (4.0 m^3) were stocked, respectively, with 120 (0.4 fish m^{-2}) and 160 (40 fish m^{-3}) juvenile pirarucu (28.03 ± 6.34 g, 11.75 ± 0.80 cm). The study was conducted for 105 days and fish were fed with commercial feed. Fish growth and plankton intake were evaluated every two weeks. Survival rate, standard length, weight gain and final weight were higher in fish reared in earthen ponds than in cages. Feed conversion of fish kept in ponds was lower (0.96 ± 0.06) than in cages (1.20 ± 0.11). The consumption of natural food organisms was observed, despite artificial feed being fed in both systems. The relative abundance of zooplankton and insects in stomachs was directly proportional to fish weight gain in ponds, and inversely proportional in cages. Higher economic efficiency rate and lower average production cost were calculated for earthen ponds. Our results indicate that the cost-benefit of the first phase grow-out of *A. gigas* is better in earthen ponds.

KEYWORDS: *Arapaima gigas,* intensive and semi-intensive production system, economic efficiency

Efeito do consumo de alimento natural sobre a recria do pirarucu em viveiros e tanques-rede

RESUMO

O pirarucu, *Arapaima gigas* é um peixe de grande importância econômica e social na Amazônia, onde é comumente produzido em viveiros. A produção de peixes em tanques-rede tem crescido no Brasil, e este sistema poderia ser uma alternativa para a produção do pirarucu, reduzindo custos e melhorando os parâmetros produtivos. Nós avaliamos a contribuição do alimento natural na produção em sistema semi-intensivo (viveiros) e intensivo (tanques-rede) e seus efeitos sobre os aspectos produtivos e econômicos do pirarucu na fase de recria. Quatro viveiros (300 m^2) e quatro tanques-rede (4,0 m^3) foram estocados, respectivamente, com 120 (0,4 peixes m^{-2}) e 160 (40 peixes m^{-3}) juvenis de pirarucu (28,03 ± 6,34 g e 11,75 ± 0,80 cm). O estudo foi conduzido por 105 dias e os peixes foram alimentados com ração comercial extrusada. Crescimento e ingestão de plâncton pelos peixes foram avaliados quinzenalmente. Sobrevivência, comprimento padrão, ganho de peso e peso final foram maiores nos peixes cultivados em viveiros. A conversão alimentar nos viveiros (0,96 ± 0,06) foi menor que nos tanques-rede (1,20 ± 0,11). Mesmo sendo ofertada ração, os pirarucus consumiram alimento natural nos dois sistemas de produção. A abundância relativa de zooplâncton e insetos nos estômagos foi diretamente proporcional ao ganho de peso nos viveiros, e inversamente proporcional nos tanques-rede. Um índice de eficiência econômica mais alto e custo médio de produção mais baixo foram calculados para os viveiros escavados. Nossos resultados indicam que o custo-benefício do cultivo de *A. gigas* durante a fase de recria é melhor em viveiros.

PALAVRAS-CHAVE: *Arapaima gigas*, sistema de produção intensivo e semi-intensivo, eficiência econômica

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INTRODUCTION

Brazilian inland aquaculture has grown significantly in recent years, and alternative fish species are warranted to diversify production. As such, studies have been conducted exploring the potential of native fish species, such as matrinxã, *Brycon cephalus* (Gunther, 1869) (Gomes *et al.* 2000); tambaqui *Colossoma macropomum* (Cuvier, 1818) (Gomes *et al.* 2006; Silva *et al.* 2007); pacu, *Piaractus mesopotamicus* Holmberg, 1887 (Abimorad *et al.* 2009); and pirarucu, *Arapaima gigas* Schinz, 1822 (Cavero *et al.* 2003; Oliveira *et al.* 2012; Menezes *et al.* 2006). Pirarucu is a fish species native to the Amazon River Basin with great potential for aquaculture because it is hardy, presents mandatory aerial breathing, and favorable national and international markets (Valladão *et al.* 2018; Valenti *et al.* 2021). Additionally, juvenile pirarucu (0.5-1.0 kg) can reach 8 kg to 10 kg in a one-year production cycle (Lima 2020). Currently, pirarucu is mostly produced in semi-intensive systems, ponds, and reservoirs (Valladão *et al.* 2018). Ponds are fertilized to increase the productivity of planktonic organisms, which constitute food sources for pirarucu during the first phase of grow-out (Lima *et al.* 2018), reducing maintenance costs. Pirarucu may also be farmed under intensive systems, in which fish are fed only with artificial feed (Ono and Kehdi 2013).

The ingestion of natural food items available in the environment can benefit fish growth, especially for native species, since the artificial feeds available may not be tailored to their nutritional requirements (Valenti *et al.* 2021). Thus, the natural food available in the farming environment plays a complementary role in their diet and may increase the performance in semi-intensive systems compared to intensive systems (Liranço *et al.* 2011). Pirarucu have been reported to ingest high amounts of planktonic organisms during the first phase of grow-out (from 10-15 cm, 10-20 g to 40-50 cm, 500-1,000 g) (Oliveira *et al* 2005; Lima *et al.* 2018). Therefore, the aim of this study was to evaluate the effect of natural food intake on pirarucu growth and economic performance during the first phase of grow-out in semi-intensive (ponds) and intensive (cages) production systems.

MATERIAL AND METHODS

The study was conducted for 105 days in cages at the Parque Aquícola Sucupira, Luís Eduardo Magalhães Hydroelectric Power Plant Reservoir (10°5'8.448"S, 48°22'0.448"W), and in earthen ponds at the Aquaculture Experimental Center of Embrapa Pesca e Aquicultura (10°8'5.067"S, 48°19'10.530"W), Palmas, Tocantins state, Brazil. The study was approved by the ethics committee for the use of animals of Embrapa Pesca e Aquicultura (CEUA/CNPASA; certificate # 50, protocol # 02/2019).

Experimental set-up

For the experiment, 1,120 pirarucu fingerlings (mean weight 28.03 ± 6.34 g and mean length 11.75 ± 0.80 cm) were purchased from a commercial fish farm (Fazenda Hidrobios, Palmas, Tocantins state, Brazil). Four 300-m^2 (15 × 30 × 1.2 m) earthen ponds were used for the semi-intensive trial. Before beginning the experiment, ponds were partially drained, and quicklime was applied at a concentration of 150 g m^{-2}. After seven days, the ponds were filled with water and fertilized with 3 g m^{-2} of urea, 6 g m^{-2} of simple superphosphate, and 10 g m^{-2} of rice bran. Maintenance fertilization was performed monthly with the same amount of fertilizers. Subsequently, fish were stocked at a density of 0.4 fry m^{-2} (Halverson 2013; Rezende and Lima, 2022), a total of 120 per pond. The water exchange rate was of 4 L min^{-1}. An anti-bird system was installed to avoid fish predation. Four 6-m^3 (2 × 2 × 1.5 m) net cages with a water volume of 4 m^3 (2 × 2 × 1 m) were used for the intensive system trial. An additional 7-mm mesh was used to prevent fish escape. Cages were covered with a shade screen (40%) to provide a better ambiance for the fish (Liranço *et al.* 2011). Cages were stocked at a density of 40 fry m^{-3} (Halverson 2013), totaling 160 fish per cage. At the beginning of the experiment, 30 additional fish were stocked per experimental unit to be sampled for stomach content analysis throughout the study.

Water quality

Water temperature, pH, and dissolved oxygen concentration were measured three times a week using a multi-parameter probe (YSI Professional Plus; YSI, Yellow Springs, Ohio, USA). Total ammonia nitrogen, nitrite, alkalinity, and hardness were measured weekly using a commercial color kit (Alfakit®, Florianopolis, Brazil). Water transparency was measured three times a week with a Secchi disk. Water transparency in the cages was measured near the mooring cable.

Pirarucu growth performance

Fish in both ponds and cages were fed daily with a commercial extruded feed for carnivorous fish species with 45% crude protein. The feeding rate varied according to fish weight: 5% (15 to 100 g), 4% (100 to 500 g) and 3% (500 to 1,000 g) biomass. Pellet size and feeding frequency also varied according to fish weight: 2.6-mm pellets four times daily for 15 to 100-g fish; 4-mm pellets four times daily for 100 to 500-g fish; and 6-mm pellets three times daily for 500 to 1,000-g fish. Uneaten feed was weighed and recorded to calculate the feed conversion. Twenty fish per experimental unit were weighed every two weeks to adjust the feeding amount. The survival rate (%) was calculated at the end of the 105-day trial. Apparent feed conversion (total feed intake/total biomass gain), standard length coefficient of variation [SLCV = (standard deviation of length/average length) × 100], final weight coefficient of variation [FWCV = (standard deviation of weight/average weight) × 100], and specific growth rate [% of live weight/day; SGR = (ln final weight - ln initial weight)/ days of cultivation × 100] were also calculated.

Plankton and stomach content

Availability of natural food organisms, i.e., phytoplankton, zooplankton, and insects, was assessed at the beginning of the experiment and every two weeks. Sampling was done using phytoplankton and zooplankton nets (20 and 68 μm, respectively). Phytoplankton and zooplankton nets were dragged over 10 m within the ponds, and for 5 min 2.0 m away from the cages. For insect collection, the content in the zooplankton net was sieved through a 270-μm screen. Samples were fixed with 4% formaldehyde and stored in 500-mL bottles. Phytoplankton and zooplankton were analyzed qualitatively and quantitatively in triplicate samples of 1 mL in a Neubauer and a Sedwick-Rafter chamber, respectively. Insects were quantitatively analyzed in triplicates of 1.0 mL samples using a Sedgewick-Rafter chamber.

Five fish from each experimental unit were sampled every two weeks (total of 30 fish throughout the study) for stomach content analysis. Fish were fasted for 24 h before sampling to allow better visualization and identification of food items in the stomach (Lima *et al.* 2018). Fish were euthanized, and their weight and length measured. Fish were separated into seven weight classes (0–100 g, 101–200 g, 201–300 g, 301–400 g, 401–600 g, 601–800 g, and 801–1,000 g). Fish stomachs were removed through an abdominal incision and stored in 10% formalin (v/v) until analysis. The stomach contents were placed in a Petri dish for qualitative and quantitative analyses under a stereomicroscope (Stemi 305, Zeiss). The content weight was calculated from the difference between the weight of the full stomach and the weight of the empty stomach (after removal of the content). The stomach content was classified into nine major categories: insects (including parts of insects, larvae, and nymphs); plants (seeds and plant tissue); phytoplankton; sediment (sand granules); feed; copepods; cladocerans; other crustaceans; and rotifers. Based on the results, the frequency of occurrence (FO) of each food item was calculated, FO being the number of stomachs where the food item occurred relative to the total number of stomachs containing any food item (Hyslop 1980). The food electivity index (*Ei*) was calculated according to Ivlev (1961), using the equation $E = (r - p) / (r + p)$, where r is the percentage of each item in the stomach contents, and p is the percentage of each item in the environment. This index ranges from –1 to +1, with positive values indicating preferred items, negative values indicating avoided items, and zero indicating food eaten at random. The relative abundance (RA) of each item was estimated as the volume of the item relative to the total volume of food present in the stomach (100%) (Silva *et al.* 2008).

Partial economic analysis

We considered only the partial operating cost (POC), defined as the amount spent on feed, fry, and inputs (fertilizers and corrective materials for ponds, and fuel used in the boat for handling fish in cages), and the gross revenue (GR) from the sale of live fish.

The economic variables were calculated according to the method described by Silva *et al.* (2003) according to equations 1 and 2:

$$POC = I + (F * P) \quad [1]$$

where POC = partial operating cost (in USD); I = expenditure on inputs (feed, fertilizers, fuel); F = number of fry; P = cost of fry;

$$GR = W \times MV \quad \text{and} \quad PNR = GR - POC \quad [2]$$

where GR = gross revenue (in USD); W = final mean weight of fish; MV = market value per kg of fish; PNR = partial net revenue (in USD).

After calculating the operating costs of each farming system, the average cost index (ACI) and the economic efficiency index (EEI) were calculated according to Barbosa *et al.* (1992) using equations 3 and 4:

$$ACI = \frac{Ctei}{Mce} \times 100 \quad [3]$$

$$EEI = \frac{Mce}{Ctei} \times 100 \quad [4]$$

where ACI = average cost index; Ctei = average cost of the farming system i; Mce = lowest average operating cost per kilogram of live weight gained between treatments; EEI = economic efficiency index.

Statistical analysis

Homogeneity of variance and normality of all response variables were confirmed with Bartlett and Shapiro-Wilk tests, respectively. Then Student's t-test ($p < 0.05$) was used to analyze differences in growth performance parameters, RA of food items in the stomach, and water quality parameters between the production systems. The RA of food items found in the stomach contents of pirarucu reared in earthen ponds and cages was compared among fish-weight classes using principal component analysis (PCA).

RESULTS

Water temperature, alkalinity, hardness, and nitrite did not differ significantly between the production systems (Table 1). Total ammonia nitrogen concentration was significantly higher in the earthen ponds than in the cages, while dissolved oxygen, transparency, and pH were higher in the cages than in the earthen ponds.

All growth performance parameters differed significantly between production systems (Table 1). Final standard length and final weight, survival, and specific growth rate were higher in the fish reared in the earthen ponds, whereas the coefficients of variation in weight and length, and feed conversion were higher in the fish reared in the cages. During the first 60 days, weight gain was similar in ponds and cages, and, from then on, became significantly higher in the ponds (Figure 1a). At the end of the 105-day trial, weight gain was 13.1% higher in pirarucu in the earthen ponds than in the cages (Table 1).

Body lesions in the fish reared in cages were observed between days 45 and 60 (data not shown). Head, caudal and pectoral fins were the most affected areas. Lesions were infected with *Aeromonas* and *Edwardsiella* according to Proietti Junior *et al.* (2017), resulting in weight loss, discoloration and, eventually, death. Fish were treated with antibiotic (TM 700; 11.85 g TM-700 per kg of live weight per day) mixed in the feed for 10 days. With the treatment, clinical signs subsided and fish recovered gradually.

The density of rotifers, copepods, cladocerans, and insects was higher in ponds than in cages throughout the trial (Figure 2). Copepods and rotifers were the most abundant organisms in both production systems. In the ponds, the density of these organisms remained relatively constant during

Table 1. Growth performance and water quality parameters (mean ± SD) during the first phase of pirarucu, *Arapaima gigas*, grow-out in earthen ponds and cages. The P-value refers to the comparison between production systems with a t-test.

Variables	Earthen ponds	Cages	P-*value*
Growth performance parameters			
Survival (%)	97.50 ± 2.04	73.91 ± 10.97	0.0060
Final standard length (cm)	43.03 ± 1.40	38.00 ± 0.75	0.0010
Final weight (g)	943.5 ± 9.01	834.78 ± 21.06	0.0001
Weight gain (g)	936.5 ±12.61	827.77 ± 25.42	0.0003
Standard length coefficient of variation (%)	10.78 ± 0.73	17.13 ± 8.71	0.0020
Final weight coefficient of variation (g)	4.80 ± 0.73	12.20 ± 3.84	0.0090
Feed conversion	0.96 ± 0.06	1.20 ± 0.11	0.0110
Specific Growth Rate (weight, %)	3.17 ± 0.01	3.06 ± 0.02	0.0020
Water quality parameters			
Temperature (°C)	28.68 ± 1.66	30.28 ± 1.52	0.1908
Dissolved oxygen (mg L^{-1})	3.79 ± 0.81	5.65 ± 0.55	0.0089
pH	7.06 ± 0.42	7.94 ± 0.32	0.0480
Total alkalinity (mg L^{-1} $CaCO_3$)	30.5 ± 6.19	36.56 ± 4.47	0.0987
Hardness (mg L^{-1} $CaCO_3$)	26.67 ± 5.84	31.41 ± 7.30	0.2980
Transparency (m)	0.37 ± 0.042	2.94 ± 0.30	0.0043
Ammonia (mg L^{-1})	0.36 ± 0.27	0.23 ± 0.32	0.0396
Nitrite (mg L^{-1})	0.00	0.00	-

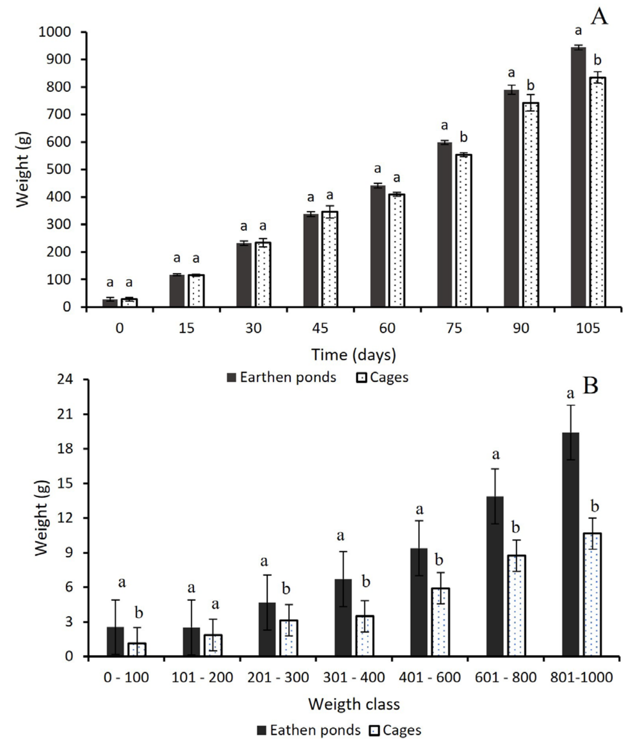

Figure 1. Body weight throughout the 105-day monitoring period (A) and weight of stomach contents per body-weight class (B) of pirarucu, *Arapaima gigas* during the first phase of grow-out in earthen ponds and net cages. Different lowercase letters indicate a significant difference between the two production systems. n = 80 per fortnight and production system (A) and n = 12 per fortnight and production system (B).

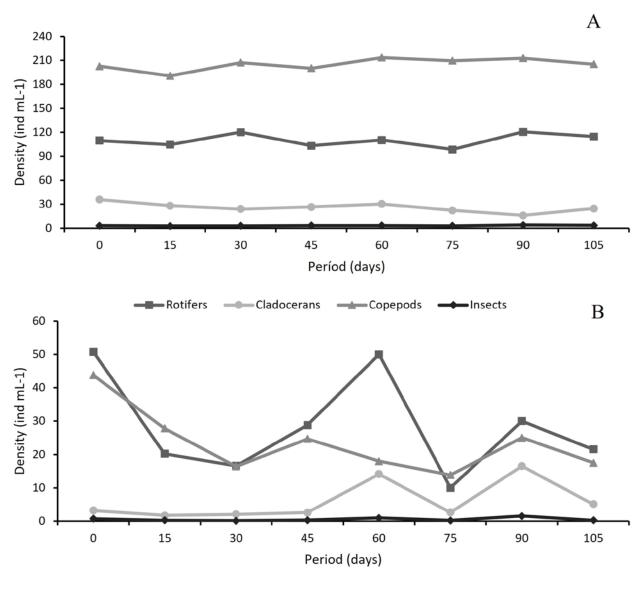

Figure 2. Density of zooplankton organisms present throughout the 105-day monitoring period during the first phase of grow-out of pirarucu, *Arapaima gigas*, in earthen ponds (A) and net cages (B).

the experimental period, whereas in the cages, the density decreased over time, and cladoceran density increased after day 45.

The weight of the stomach content of fish reared in the ponds was higher than that of cage fishes in all weight classes (Figure 1b). Cladoceran, copepod, and rotifer relative abundance was significantly higher in the stomach of pirarucu reared in ponds (Table 2). The highest RA of these food items occurred in small fish, and gradually reduced as fish grew. In the cages, RA of cladocerans, copepods and rotifers did not exceed 7%. Insect RA was higher in ponds, where this item was present in all weight classes.

Insect RA was higher in larger fish and in ponds. Other crustaceans accounted for less than 4% of all stomach contents in both production systems, being absent in fish < 200 g in the ponds and < 800 g in the cages. There was no difference in the RA of phytoplankton between the production systems. The RA of artificial feed was higher in the cages in all weight classes and increased as fish grew. Artificial feed was found in most sampled stomachs, even after the fish fasted for 24h. RA of plants was significantly higher in the ponds than the cages in all weight classes. In the ponds, plant RA was ~10% in all weight classes, and less than 2.5% in the cages. Sediment was present in all stomachs and all weight classes in both production systems; RA of sediment was significantly higher in the cages (~65% of all stomach contents) than in ponds.

The frequency of occurrence of natural food items was generally higher in the ponds than in the cages (Table 3). The FO of cladocerans, copepods, rotifers, and phytoplankton decreased with the increase in fish weight in both production systems (Table 3). In contrast, FO of insects and artificial feed increased with fish weight. FO of plants increased with fish weight in the ponds; conversely, but plants were only found in stomachs of small fish in the cages. In both systems, other crustaceans occurred in large fish, whereas sediments were frequent in all sizes.

For the ponds, the first two axes of the PCA represented 52.8% of the data variability (Figure 3). For axis 1, sediment (0.37) and feed (0.28) were the primary positively related descriptors, while cladocerans (–0.46) and rotifers (–0.44) were the main negatively related descriptors. For axis 2, sediment (0.36), and feed (0.59) were the primary positively related descriptors, while insects (–0.65) and other crustaceans (–0.59) were negatively related. For the cages, the first two axes of the PCA represented 45.6% of the data variability. For axis 1, copepods (0.47) and rotifers (0.47) were the primary

Table 2. Mean relative abundance (%) of food items found in the stomach contents of pirarucu, *Arapaima gigas* of different weight classes throughout 105 monitoring days during the first phase of grow-out in earthen ponds (EP) and net cages (C). Different uppercase letters for a food item in a body-weight class indicate significant differences between the two-production systems. n = sample size.

Food items	System	Weight class (g)						
		0–100	101–200	201–300	301–400	401–600	601–800	801–1.000
Cladocerans	EP	25.0 ± 3.1^{A}	27.8 ± 5.9^{A}	16.5 ± 3.8^{A}	15.2 ± 6.6^{A}	9.0 ± 6.4^{A}	4.4 ± 1.8^{A}	4.4 ± 4.2^{A}
	C	3.7 ± 1.1^{B}	3.1 ± 1.7^{B}	4.3 ± 3.5^{B}	5.4 ± 2.0^{B}	4.7 ± 3.2^{B}	4.2 ± 4.1^{B}	2.2 ± 0.8^{B}
Copepods	EP	15.2 ± 3.3^{A}	11.5 ± 2.1^{A}	9.9 ± 5.9^{A}	9.1 ± 3.0^{A}	6.0 ± 2.5^{A}	3.9 ± 2.2^{A}	6.0 ± 2.5^{A}
	C	4.3 ± 1.7^{B}	4.9 ± 2.7^{B}	4.6 ± 2.5^{B}	6.7 ± 2.7^{B}	3.5 ± 2.0^{B}	1.6 ± 0.2^{B}	2.0 ± 0.8^{B}
Rotifers	EP	16.8 ± 3.8^{A}	13.7 ± 6.4^{A}	9.5 ± 4.7^{A}	5.0 ± 2.8^{A}	5.3 ± 2.6^{A}	2.0 ± 1.3^{A}	3.4 ± 2.3^{A}
	C	4.7 ± 3.1^{B}	4.7 ± 2.1^{B}	3.4 ± 2.3^{B}	6.0 ± 3.8^{B}	3.9 ± 2.6^{B}	2.2 ± 1.0^{B}	1.9 ± 0.8^{B}
Insects	EP	9.9 ± 6.2^{A}	12.0 ± 4.2^{A}	12.9 ± 4.9^{A}	13.1 ± 10.8^{A}	17.9 ± 4.5^{A}	17.5 ± 5.3^{A}	18.8 ± 3.1^{A}
	C	0.0 ± 0.0^{B}	2.2 ± 0.7^{B}	2.8 ± 1.9^{B}	2.8 ± 1.4^{B}	2.9 ± 1.7^{B}	3.0 ± 1.1^{B}	3.6 ± 0.8^{B}
Phytoplankton	EP	2.7 ± 1.3^{A}	3.4 ± 2.0^{A}	2.4 ± 1.1^{A}	2.1 ± 0.9^{A}	1.8 ± 0.8^{A}	1.4 ± 0.3^{A}	1.4 ± 0.3^{A}
	C	3.7 ± 1.4^{A}	2.6 ± 0.9^{A}	2.7 ± 0.8^{A}	2.6 ± 1.0^{A}	2.4 ± 1.4^{A}	1.7 ± 0.7^{A}	1.5 ± 0.1^{A}
Other crustaceans	EP	0.0 ± 0.0^{A}	0.0 ± 0.0^{A}	2.3 ± 1.0^{A}	0.0 ± 0.0^{A}	1.5 ± 0.2^{A}	3.6 ± 3.8^{A}	3.6 ± 0.9^{A}
	C	0.0 ± 0.0^{A}	0.0 ± 0.0^{A}	0.0 ± 0.0^{B}	0.0 ± 0.0^{A}	0.0 ± 0.0^{B}	0.0 ± 0.0^{A}	1.6 ± 0.0^{B}
Feed	EP	5.9 ± 0.2^{A}	7.5 ± 2.6^{A}	10.6 ± 5.3^{A}	16.4 ± 7.4^{A}	17.8 ± 4.0^{A}	17.0 ± 6.0^{A}	15.4 ± 7.0^{A}
	C	13.0 ± 4.6	12.3 ± 5.0	15.2 ± 3.4	18.4 ± 5.2	19.0 ± 8.6	23.3 ± 7.0	24.0 ± 6.4
Plants	EP	7.3 ± 2.1^{A}	9.5 ± 3.6^{A}	9.4 ± 6.4^{A}	9.2 ± 7.9^{A}	9.4 ± 5.0^{A}	9.9 ± 4.9^{A}	9.6 ± 5.8^{A}
	C	2.5 ± 0.1^{B}	1.7 ± 0.3^{B}	0.0 ± 0.0^{B}	0.0 ± 0.0^{B}	0.0 ± 0.8^{B}	0.0 ± 0.0^{B}	0.0 ± 0.0^{B}
Sediment	EP	17.1 ± 8.7^{A}	14.1 ± 9.8^{A}	29.4 ± 7.7^{A}	30.2 ± 10.2^{A}	31.3 ± 10.3^{A}	37.8 ± 12.8^{A}	35.4 ± 11.7^{A}
	C	68.1 ± 8.1^{B}	68.0 ± 7.5^{B}	57.8 ± 12.6^{B}	61.2 ± 12.2^{B}	65.2 ± 9.5^{B}	64.2 ± 8.9^{B}	68.4 ± 5.5^{B}
n	EP	4	9	13	12	18	12	16
	C	4	10	17	5	25	9	14

positively related descriptors, while feed (–0.37) and other crustaceans (–0.13) were the main negatively related. For axis 2, feed (0.60) and rotifers (0.19) were the primary positively related descriptors, while sediment (–0.73) and phytoplankton (–0.07) were negatively related. Diet of fish < 300 g reared in the ponds differed from that of fish of 300-600 g and > 600 g, with little overlap. However, in cages, there was a more significant overlap of natural food items in fish < 300 g and 300-600 g, whereas fish > 600 g were more distanced in the multivariate space.

The presence of cladocerans, copepods, rotifers, and insects in the pond water varied throghout the study period. In the ponds, selectivity was high for insects in fish above 100 g, and for cladocerans in smaller fish, while copepods and cladocerans tended to be avoided by larger fish (Figure 4a). In the cages, selectivity was high for copepods by smaller fish, while rotifers seemed to be avoided by fish smaller than 100 g (Figure 4b).

Except for fertilizers, correctives and fuel, the inputs of pond and cage production were similar (Table 4). Fry (73% in ponds and 80% in cages) and feed (26% in ponds and 33% in cages) accounted for most of the production cost in both production systems. The partial operational cost of farming pirarucu was higher in the cages than in the ponds, while gross revenue and partial net revenue were higher in the ponds than in the cages (Table 5). Mean production was lower in the cages, and, as a result, the ACI were higher in the cages than in the ponds. The EEI were better for ponds than for cages.

DISCUSSION

In ponds, water exchange is absent or low, and the accumulation of nitrogen compounds results from the decomposition of leftover feed, animal excreta, and fertilizers applied to maintain planktonic organisms (Boyd 1990). Conversely, in reservoirs, due to the large volume of water and frequent water renewal, the capacity to dilute effluents from fish production in cages is high (Matos *et al*. 2016). This explains the differences observed in the concentration of ammonia between treatments, with the higher values in ponds, even though they have remained within the range for pirarucu (Ono and Khedi 2013). The large volume of water in the reservoirs, associated with high renewal rates, provides higher water transparency and oxygen availability (Lima *et al*. 2013). In the ponds, the accumulation of organic matter, added to the fertilization management, results in high primary productivity and a consequent decrease in transparency and significant variation in oxygen concentration, which can reach critical values depending on the fish and plankton biomass (Boyd 1990).

Overall, pirarucu showed better growth performance when reared in ponds than in cages, possibly because of the greater availability of natural food, its consumption by the fish, and the greater availability of space. Nonetheless, significant differences between treatments only occurred after 75 days of the trial, as reported by Lirança *et al*. (2011) and Scorvo Filho *et al*. (2008) for *Pseudoplatystoma corruscans* (Spix & Agassiz, 1829). Higher intake of natural food items by pirarucu kept

Table 3. Frequency of occurrence (%) of food items found in the stomach contents of pirarucu, *Arapaima gigas* raised for 105 days during the first phase of grow-out in earthen ponds (EP) and net cages (C).

Food items	System	Weight class (g)						
		0–100	101–200	201–300	301–400	401–600	601–800	801–1,000
Cladocerans	EP	100.0	100.0	100.0	91.6	88.8	83.3	81.2
	C	100.0	70.0	82.3	80.0	88.0	55.6	78.6
Copepods	EP	100.0	100.0	92.3	91.7	88.9	83.3	75.0
	C	100.0	75.0	82.3	80.0	72.0	44.4	71.4
Rotifers	EP	100.0	100.0	100.0	75.0	72.2	58.3	56.2
	C	100.0	80.0	70.6	70.0	68.0	22.2	54.3
Insects	EP	50.0	84.9	84.6	85.0	88.9	91.7	97.5
	C	0.0	40.0	45.3	50.0	52.0	54.2	58.4
Phytoplankton	EP	100.0	100.0	100.0	100.0	83.3	83.3	56.2
	C	75.0	70.0	94.1	80.0	84.0	44.4	64.3
Other crustaceans	EP	0.0	0.0	0.0	0.0	16.7	16.7	18.7
	C	0.0	0.0	0.0	0.0	0.0	0.0	7.1
Feed	EP	50.0	75.8	76.9	83.3	88.9	91.7	95.0
	C	70.0	77.0	78.8	100.0	100.0	100.0	100.0
Plants	EP	75.0	88.8	92.3	91.6	94.4	100.0	100.0
	C	50.0	30.0	0.0	0.0	0.0	0.0	0.0
Sediment	EP	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	C	100.0	100.0	100.0	100.0	100.0	100.0	100.0

in ponds may explain the lower artificial feed intake and better feed conversion value. The restricted access to natural food in cages resulted in poor fish performance. The complementary role of natural food items in fish diet has already been reported (Sipaúba-Braga *et al.* 2007; Lima *et al.* 2018) and it may constitute one of the advantages of semi-intensive production systems (Crepaldi *et al.* 2006). Feed conversion in ponds was lower than the value reported by Pereira-Filho *et al.* (2003) in a 12-month trial in ponds (1.51:1.0). This may be due to the shorter experimental period (105 days) in our study, covering only the first phase of grow-out, when feed conversion tends to be better (Brandão *et al.* 2004). In cages, feed conversion

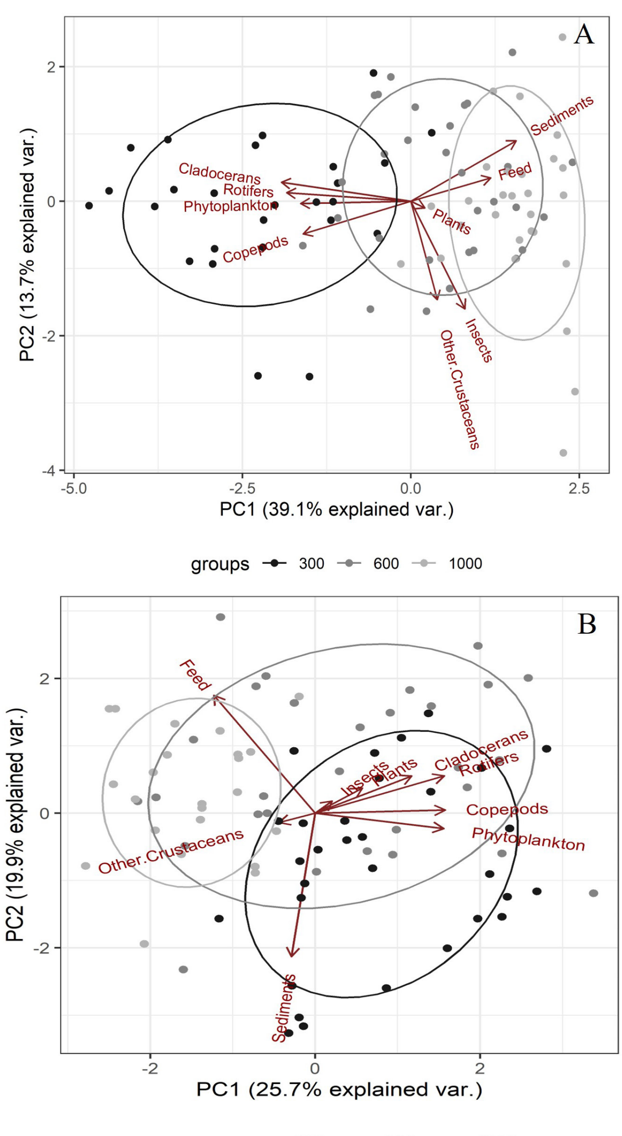

Figure 3. Scores of the principal component analysis of the relative abundance of food items found in the stomach content of pirarucu, *Arapaima gigas*, grouped by body-weight class and reared in earthen ponds (A) and net cages (B) during the first grow-out phase. Numbers in the axis titles are the percentage of variance explained by the axis. This figure is in color in the electronic version.

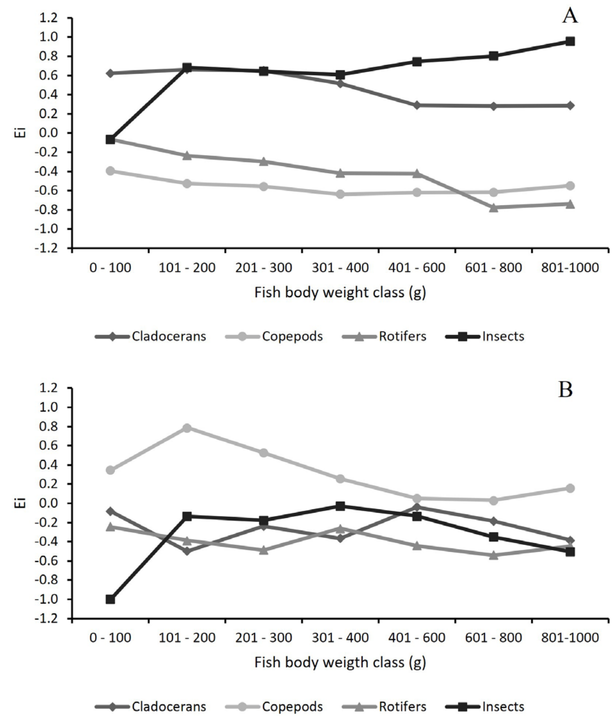

Figure 4. Food electivity index (*Ei*) of pirarucu, *Arapaima gigas* in ponds (A) and cages (B) per body-weight class.

Table 4. Values of purchase of inputs and sale of products used during the first phase of grow-out of *Arapaima gigas* in earthen ponds and net cages for 105 days. Prices charged in Palmas (Tocantins, Brazil) in August 2019. Values are in US dollars (USD 1 = BRL 4.14).

Item	Unit value (USD)	Total cost/revenue	
		Earthen ponds	Net cages
Feed 2.6 mm (kg)	1.14	6.31	7.89
Feed 4.0 mm (kg)	0.93	49.54	54.31
Feed 6.0 mm (kg)	0.85	71.77	68.12
Fertilizers and correctives			
Urea (kg)	1.05	3.77	-
Super phosphate (kg)	0.77	5.57	-
Rice bran (kg)	0.34	4.12	-
Quick lime (kg)	0.43	19.46	-
Fuel (liter)	1.09	-	17.93
Fingerlings (unit)	3.62	434.78	579.71
Selling price (kg)	10.87	1199.40	1071.93

Table 5. Economic evaluation of the first phase of pirarucu, *Arapaima gigas* grow-out in earthen ponds and net cages for 105 days. Prices practiced in Palmas (Tocantins, Brazil) in August 2019. Values are in US dollar (USD 1 = BRL 4.14).

Parameter	Earthen ponds	Net cages
Partial operational cost (USD)	595.30	728.00
Gross revenue (USD)	1199.40	1071.90
Partial net revenue (USD)	604.10	531.20
Mean production (kg of fish)	110.40	98.70
Relative partial operational cost (USD per kg of fish)	5.40	5.92
Average cost index (% ACI)	103	112
Economic efficiency index (% EEI)	97.5	89.0

was similar to that reported by Oliveira *et al.* (2012) after a 140-day trial in cages (1.2:1.0).

Juvenile pirarucu show gregarious behavior when in captivity, establishing hierarchy and increasing growth heterogeneity (Oliveira *et al.* 2012), as the dominant fish feed first and prevent others from feeding (Huntingford and Leaniz 1997). This heterogeneity is even more evident in intensive systems, in which high densities facilitate animal encounters (Santos *et al.* 2016). Such size heterogeneity was observed in the present study, especially in fish kept in cages, where higher density may have aggravated it (Cavero *et al.* 2003; Lima 2020).

The survival rate was higher in fish produced in the ponds than in the cages, where mortality was associated with an outbreak of bacterial disease, which is common in intensive production systems (Woo *et al.* 2014). Nevertheless, Menezes *et al.* (2006) and Oliveira *et al.* (2012) did not report health issues for pirarucu reared in cages, with survival rates of 91.7% and 94.7%, respectively. Lower survival in cages was also reported for tilapia and *P. corruscans* (Liranço *et al.* 2011; Santos *et al.* 2016) when compared to ponds. According to Pavanelli *et al.* (2002), high stocking densities in cages, poor water quality and inadequate handling of food, lead to accumulation of organic matter in the cages, which in turn becomes substrate for bacterial growth. In the present study, pirarucu survival in ponds was high, and similar to that observed by Pereira-Filho *et al.* (2003) in ponds.

The absence of pirarucu with empty stomachs in both ponds and cages corroborates the species' characteristic consumption of natural food items, as reported for fish in the wild (Oliveira *et al.* 2005) and in captivity (Lima *et al.* 2008). However, natural food intake decreased over time, as the amount found in stomachs did not increase proportionally with fish growth. This may be due to changes in food preference, and/or to the absence or low availability of new food items in the farming environment (Lima *et al.* 2018; Makrakis *et al.* 2005). Pirarucu can regulate nutrient uptake, ingesting artificial feed and natural food items simultaneously and in different amounts, selecting items with high protein and energy content, such as zooplankton (Lima *et al.* 2018). Zooplankton organisms are excellent natural food items for carnivorous fish, especially during the early life stages (Winemiller 1989), which explains the zooplankton intake by juvenile pirarucu in all weight classes, both in ponds and cages, with the highest abundance and frequency of cladocerans, copepods, and of rotifers in the initial stages in ponds. The presence of natural food items in stomachs of fish reared in cages demonstrates the importance of natural food items in intensive systems, which has also been reported for other cage-reared species, such as *Aristichthys nobilis* (Richardson 1845) (Cremer and Smitherman 1980) and *Oreochromis mortimeri* (Trewavas 1966) (Norberg 1999; Huchette *et al.* 2000). Insects were also consumed by all weight groups, and insect frequency of occurrence and relative abundance increased with fish growth in the two production systems, showing the fish preference for larger prey as they grew. Insects can supply significant amounts of proteins and lipids (Barroso *et al.* 2014), representing a valuable source of nutrients while replacing the smaller prey of the early stages (Lima *et al.* 2018).

The selectivity of food items consumed by a species varies according to their quality, palatability, and environmental abundance (Zavala-Camin 1996). Size is another factor that determines the selection and consumption of food items, as, by natural selection, large fish consume large items (Hagiwara *et al.* 2007; Shaw *et al.* 2003). In ponds, fish were mostly selective for cladocerans and insects, which corroborates the findings by Oliveira *et al.* (2005) and Lima *et al.* (2018), who also observed pirarucu preference for these items in the natural environment and in ponds, respectively. These studies showed that pirarucu maintained its food preferences, even when fed with artificial feed in farming conditions. Food selectivity in fish is uniform among individuals of the same size and species (Zavala-Carmin 1996), yet the selectivity in juvenile pirarucu was influenced by the production system, as pirarucu kept in cages showed high selectivity for copepods. Changes in feeding habits of fish species may occur due to interactions among environmental factors that influence the selection of food items (Teixeira and Gurgel 2002). In our study, restricted mobility in the cages may have influenced prey selection.

Selectivity for natural food items changed as the pirarucu grew, while, at the same time, the FO and RA of artificial feed in the stomachs increased in both systems, indicating that, when nutritional requirements cannot be met, fish become increasingly dependent on artificial feeds (Makrakis *et al.* 2005). In addition, the digestion process is faster in smaller animals (Booth *et al.* 2008), which can also explain why artificial feed was less frequently found in the stomachs of smaller pirarucu.

Fry and feed accounted for most of the production cost, corroborating the findings of Muñoz *et al.* (2015) and Pedroza Filho *et al.* (2016), who estimated that fry and feed accounted for 25% and 56%, respectively, of the effective operating costs in pirarucu production in earth ponds. The low supply in the market is the main reason for the high price of pirarucu fry (Guerreiro *et al.* 2015). The large share of feed in the production cost is inherent to fish production, but fry rarely has a high impact on production costs for other species (Silva *et al.* 2003), except for carnivorous fish (Campos 2005). The best financial results in the first phase of pirarucu grow-out were obtained for fish raised in ponds. The values were lower than those reported by Muñoz *et al.* (2015), who found an effective operating cost of USD 4.33 per kg of fish (values updated by the IGPM-M index in Jan 2022, USD 1 = BRL 3.95) for the entire grow-out phase. This lower cost may be related to the longer duration of the production phase evaluated by Muñoz *et al.* (2015), as the cost of fry is diluted along the production cycle, eventually decreasing the total operating costs. ACI was lower and EEI was higher in the ponds than in the cages, as reported by Liranço *et al.* (2011) for *P. corruscans* farming, corroborating the economic advantage of ponds when considering only the operational costs.

CONCLUSIONS

Ponds were the best production system for *Arapaima gigas* during the first phase of grow-out, based on growth performance and economic feasibility analysis. Juvenile *Arapaima gigas* up to 1 kg weight consumed natural food when grown both in cages and ponds, with a more significant contribution of natural food in ponds, despite the artificial feed offered. Yet the production system influenced the preference of pirarucu for natural foods, with a higher selectivity for cladocerans and insects in ponds, and for copepods in cages.

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