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Research Article

Small-scale fish farming in seasonal ponds in Brazil: technical and economic characterization

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ABSTRACT. The inclusion of aquaculture in household agriculture has been related as an opportunity of product and income diversification as wells as to increase food security for farmers. Small-scale fish production has increased in Brazil, even in regions with a pronounced dry season. However, there is no information about the characteristics and technical and economic viability of aquaculture under these conditions. This study was carried out with the objective to characterize the production of tambatinga (♀*Colossoma macropomum* × ♂*Piaractus brachypomus*) in water deficit conditions in Tocantins State, Brazil. The study revealed that it is technically possible and economically feasible to produce tambatinga in seasonal ponds. Worth noting was the adaptability of the hybrids which showed a suitable growth and tolerance to the poor water quality conditions. However, in order to achieve production success and financial returns, the adoption of the following procedures are suggested: a) fish stocking as soon as the rainy period starts, b) use of larger juveniles to achieve a higher final weight, c) adoption of pond liming and fertilizing practices previous to stocking, d) water quality monitoring, e) evaluate fish growing performance, f) partial harvesting during the production cycle, and g) total harvesting at the end of the rainy season.

Keywords: *Colossoma macropomum*, *Piaractus brachypomus*, household agriculture, deficit hydric, tambatinga, production.

INTRODUCTION

Family agriculture predominates in rural farms in Brazil (IBGE, 2007). In this type of production, farmers are responsible for production management, emphasize production diversification, and use family labor, which may be supplemented with hired labor (MDS, 2014). Production diversification was originally adopted to meet the subsistence needs of the family and is currently used as a strategy to reduce risk and uncertainty (Buainain *et al.*, 2003) by generating income throughout the year, depending on the different crops and productions adopted (Lima, 2008).

In this sense, fish farming stands out as a possible alternative for inclusion in family agriculture due to its high productivity and importance in fighting food insecurity by increasing the consumption of fish, which has high nutritional value, and by supplementing the family income, decreasing poverty, and promoting social and economic development (Ahmed & Lorica, 2002; Baccarin *et al.*, 2009; Kawarazuka & Béné, 2010; FAO, 2011). In addition, it contributes to the better use of the farms' natural resources and may increase family welfare if used for leisure (Kubitza & Ono, 2010).

Fish farming has been adopted in family farms in several regions of Brazil (Tinoco, 2006; Baccarin *et al.*, 2009; Cardoso *et al.*, 2009). Many of these farms are located in regions with long periods of water deficit, which directly affect aquaculture production (Tucci *et al.*, 2001; INMET, 2014). Due to the seasonality of water availability, farmers seek production alternatives such as shorter fish production cycles (Gupta, 2001; Roos *et al.*, 2002). However, although fish farming is strongly affected by water availability, it shows promise even in locations with water restrictions. This is the case of in the west-central region of the state of Tocantins, Brazil, where family fish farming has been increasing greatly over the last few years as a food and

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income alternative, promoted by the favorable climate (high temperature and rainfall during the rainy season) and the potential for developing aquaculture in this state (Silva *et al.*, 2013; Torati *et al.*, 2014). Roundfish is the second most produced fish group in Brazil (Rabobank, 2013; IBGE, 2014). The group is represented by the species *Piaractus brachypomus* (Cuvier, 1818) (pirapitinga), *P. mesopotamicus* Holmberg, 1887, *Colossoma macropomum* (Cuvier, 1816) (tambaqui), and their respective hybrids and is the most common fish group produced in seasonal ponds in this region. In this group, the tambatinga hybrid (♀ *C. macropomum* x ♂ *P. brachypomus*) is notable. Although little studied, this hybrid is widely produced in the north and west-central regions of Brazil because it combines desirable characteristics from the two parental species such as the fast growth rate of the tambaqui and the high deposition of the dorsal muscle of the pirapitinga (Hashimoto *et al.*, 2012). Tambatinga reaches between 1.5 and 2 kg in one year in regions without a water deficit, but its production potential in seasonal ponds is not known.

To identify technological and socioeconomic improvements and formulate incentive policies to fish farming, it is important to characterize fish production systems (Nhan *et al.*, 2006; FAO, 2011). Using a participatory approach, production systems can be characterized and analyzed together with the farmers involved, integrating their social, cultural, and economic reality (Townsley, 1996; Silva *et al.*, 2013). The present study monitored a production cycle of tambatinga in family farms located in the west-central region of Tocantins, with the aim of characterizing fish production in regions with long periods of water deficit and evaluating the economic contribution of fish production to farmers.

MATERIALS AND METHODS

Study site and approach

The west-central region of the state of Tocantins -the municipalities of Divinópolis and Abreulândia (Fig. 1)- was chosen for study due to its history of inclusion of fish farming in family agriculture and long periods of water deficit (about six months), where fish farming characteristically occurs in seasonal ponds (Gupta, 2001).

The study was based on a preliminary participatory appraisal performed to understand the dynamics of local family fish farming (Silva *et al.*, 2013). Visits were conducted before the study began to raise awareness and engage the local farmers in helping with the monitoring. The entire study was conducted using a participatory approach, where the local farmers actively participated in the selection of the fish farms to be monitored and in the fish production, definition of the production parameters, and data collection and recording.

Selection of fish farms to be monitored

A workshop was held with local farmers during which the aims of the study and the specific activities that would have to be performed were explained. Following the workshop, the farmers themselves indicated seven farms to be monitored during one fish production cycle, taking into consideration the interest of each farmer in participating in the study and the availability of the farmers to perform the necessary activities. In a second workshop directed only at the selected farmers, the farmers were trained on how to complete the forms, use instruments, and monitor production using the necessary techniques, according to the learning-by-doing principle (De *et al.*, 2012). This was followed by individual training at the farms, as described by Lima *et al.* (2014).

Production monitoring

To allow comparisons among the different production units, the following technical production aspects were standardized with the help of the farmers: a) date of the beginning of monitoring, based on the time from when the seasonal ponds had sufficient water to begin fish farming, b) fish species, to facilitate comparisons regarding fish performance and economic aspects, and c) stocking density, considering the region's history of total mortality due to high stocking densities (which would make monitoring impossible), water availability throughout the year, production characteristics of the species, and fish consumption by the family during the production cycle.

Seven family farms, with nine seasonal ponds, were monitored (Table 1). Production began on 12 December 2012, using tambatinga juveniles weighing 1.49 ± 0.60 g. Fish fry were obtained from a fish farm located in the study region in the municipality of Brejinho de Nazaré, transported in plastic containers, and acclimatized to the ponds. The initial reference stocking density was 1 fish m^{-2} and was adjusted to a higher density (1.22 ± 0.33 fish m^{-2}) when the producer expressed interest in consuming fish during the production cycle (farms A, B, D, and E) or lower when they expressed a lack of financial ability to maintain a large number of fish (farms C and F) (Table 1).

During the production cycle, the fish were fed commercial feed for omnivorous fish. Only two farmers (C and F) reported using other ingredients (ground soybean, corn, and bean), and these were used

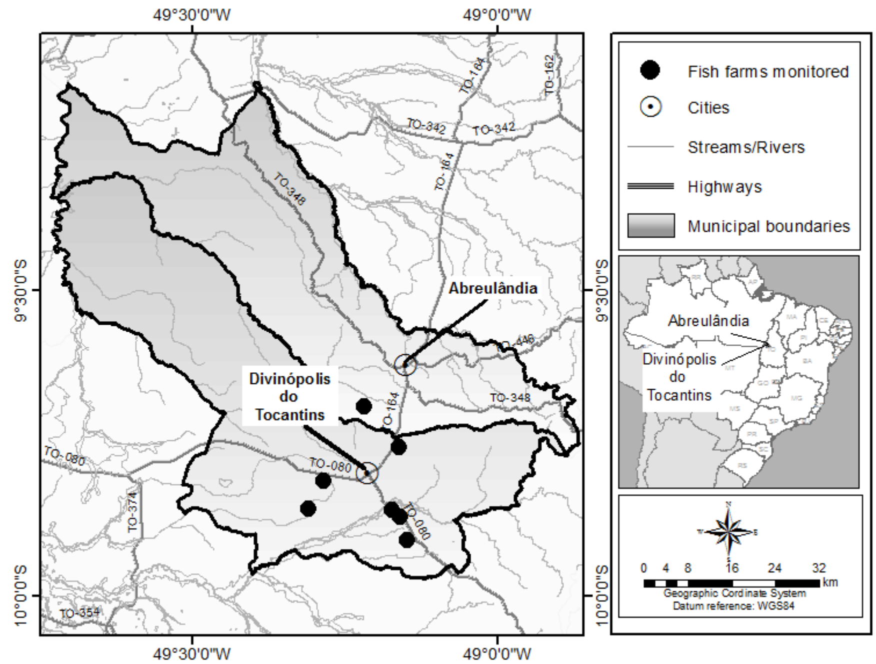

Figure 1. Location of the study site.

Table 1. Seasonal ponds monitored during one production cycle of tambatinga (♀*Colossoma macropomum x* ♂*Piaractus brachypomus*). Pond surface area, stocking density, water quality parameters (mean ± standard deviation), and fish mortality for the different studied production units. NQ: not quantified; *Different letters indicate different farms, and different numbers indicate more than one production unit within a given farm. **Collection of the dissolved oxygen data began on 16 May 2013. ***All the production units presented toxic ammonia below 0.02 mg L^{-1}.

Production unit*	Pond surface area (m^2)	Stocking density (fish m^{-2})	Temperature (°C)	Water transparency (cm)	Dissolved oxygen (mg L^{-1})***	pH	Total ammonia (mg L^{-1})*	CO_2 (mg L-1)	Alkalinity (mg L^{-1})	Nitrite (mg L^{-1})	Mortality (%)	Period of data collection	
												Initial	Final
A1	192	1.56	27.6 ± 1.2	91.2 ± 37.5	1.2 ± 0.9	6.4 ± 0.3	0.5 ± 0.2	17.9 ± 6.3	21.3 ± 3.6	0.1 ± 0.3	0.33	12/16/2012	08/31/2013
A2	288	1.46	27.4 ± 1.3	50.6 ± 15.4	2.6 ± 1.2	6.8 ± 0.4	0.6 ± 0.0	9.8 ± 4.4	25.1 ± 8.0	0.0 ± 0.0	10.95	12/17/2012	08/31/2013
B1	250	1.10	27.4 ± 0.7	63.6 ± 19.0	3.4 ± 0.6	6.0 ± 0.2	0.6 ± 0.2	14.4 ± 2.4	9.7 ± 4.9	0.2 ± 0.1	0.36	12/15/2012	06/16/2013
B2	270	1.03	27.4 ± 0.8	66.4 ± 12.1	3.9 ± 0.5	6.0 ± 0.3	0.5 ± 0.2	14.8 ± 3.0	10.4 ± 5.6	0.2 ± 0.1	47.67	12/15/2012	06/16/2013
C	800	0.63	28.5 ± 1.0	51.4 ± 17.2	2.8 ± 1.0	7.0 ± 0.0	0.6 ± 0.0	6.1 ± 0.5	8.4 ± 2.0	0.0 ± 0.0	3.35	02/07/2013	06/02/2013
D	236	1.53	26.5 ± 2.6	33.4 ± 6.2	NQ	6.9 ± 0.6	1.5 ± 2.3	20 ± 9.3	50.5 ± 22.0	0.3 ± 0.2	0	12/15/2012	07/08/2013
E	200	1.00	28.3 ± 1.1	57.2 ± 18.6	1.8 ± 0.5	6.7 ± 0.5	0.6 ± 0.2	16.4 ± 3.5	31.2 ± 7.3	0.0 ± 0.0	2.5	12/15/2012	08/10/2013
F	11.555	0.14	28.9 ± 1.1	48.2 ± 8.6	NQ	6.5 ± 0.5	0.6 ± 0.0	9.7 ± 0.7	21.3 ± 1.2	0.0 ± 0.0	7.58	01/14/2013	08/10/2013
G	125	1.44	31.5 ± 1.6	NQ	NQ	8.0 ± 1.0	0.3 ± 0.3	2.5 ± 3.0	43.5 ± 24.0	0.3 ± 0.2	1.11	12/16/2012	03/10/2013

for less than 15 days. The following technical and economic data were collected in partnership with the farmers:

a. Fish farming expenses: the use of inputs, purchased and not purchased (acquired from the farm);
b. Pond liming and fertilization before stocking and during the production cycle: type and amount of input applied in each procedure;
c. Water quality parameters, measured daily: temperature (in the morning) was measured using a thermometer, transparency (between 11:00 h AM and 12:00 h PM) using a Secchi disk, and pH (in the morning) using a water analysis kit. Dissolved oxygen was initially measured using a water analysis kit, and five months after the beginning of monitoring, in six production units, using digital oximeters;
d. Water quality parameters, measured weekly in the morning: total ammonia, carbon dioxide, total alkalinity, and nitrite, using a water analysis kit;
e. Daily feeding: quantity and type of feed or food offered;
f. Rainfall: only its occurrence or absence was recorded;
g. Decrease in the number of fish at the fish farm: due to mortality, consumption, or sale; and
h. Monthly biometry measurements: fish weight (in groups), standard length, and health.

The monitored farms were visited monthly for reviewing, discussing, and monitoring the data collected by the farmers. The biometric measurements were performed during these visits, with the help of the research team. In addition, with the aim of stimulating the exchange of experiences between local farmers, participating or not in the study, monthly workshops were held to discuss fish farming, including its difficulties and solutions.

Economic analysis

Because the farmers on some fish farms harvested the fish when the fish began to lose weight, an economic analysis was performed, taking into consideration two time periods: 1) the actual period, which corresponded to the total production cycle, and 2) the ideal period, which corresponded to the ideal harvest time, *i.e.*, the time when the fish was at the highest weight in each fish farm. For fish farms where the harvest was performed when the fish were at their highest weight, the ideal period was not estimated.

The production cost was calculated considering the components described by Matsunaga *et al.* (1976): the effective operational cost (EOC): the expenses of fish fry, feed, correctives, fertilizers, and maintenance of machinery and equipment; the total operational cost (TOC): the effective operational cost plus expenses with the depreciation of improvements; and the total cost (TC): the total operational cost plus the opportunity cost of labor.

The indicators of economic viability of production used were gross income (GI): income from the production sales; net margin (NM): the ratio between the net income and total operational cost; and profit (P): the difference between the gross income and total production costs, including all production factors (Scorvo-Filho *et al.*, 2004).

Labor was calculated as the opportunity cost because services were performed by the farmers themselves, and no outside labor was hired. Labor was therefore considered as that of a multifunctional worker, working for one hour per day during the fish production cycle, plus a total of 16 h for fish stocking and harvest. The value of work hours was calculated based on the current minimum wage.

Statistical analysis

All statistical analyses were performed using the R software (R Core Team, 2013). The different production units were divided into three groups: I) with liming and fertilization, II) only with fertilization, and III) without pond preparation procedures (Karim *et al.*, 2011). Differences in fish growth during the initial growth phase between the three groups of production units were tested using analysis of variance, considering the categorized production units as the independent variable, followed by Tukey's test, at $P < 0.05$. Relations among the different water quality parameters measured, time of cultivation and fish weight were analyzed using Pearson's correlation coefficient. Multiple stepwise linear regression was used to identify which variables best explained the variance in fish weight.

RESULTS

Fish farm characteristics

Most fish farms studied were set in ponds originally built as water sources for livestock, serving as reservoirs for direct or indirect (resulting from water table rising) water catchment, without water entrance or exit, with depth varying between 1.5 and 4.0 m and a mean area of 223 m^2 (except on farms C and F) (Table 1).

Time of cultivation

Cultivation began approximately 30 to 45 days after the first rains in the region when the seasonal ponds contained sufficient water to begin fish farming. Water availability became limited in most farms at the beginning of the dry season. The end of the production cycle varied for different production units, extending to between 170 and 270 days of cultivation, depending on the water dynamics of each production unit. High soil drainage in production unit G made fish production impracticable, and the production cycle was terminated during the third month of cultivation.

Water quality and rainfall

The mean values for the water quality parameters, measured daily or weekly, are presented in Table 1. Production unit D had high mean ammonia concentration, and production unit G had high pH. Water transparency could not be measured in production unit G due to high soil drainage, low fertility, and a low water level. Units B1, B2, and C had low alkalinity.

The variations in water quality parameters along the production cycle are presented in Fig. 2. Temperature and pH were the only relatively stable parameters throughout the production cycle, exhibiting very little variation compared to the remaining parameters. Water transparency was initially high in most production units and gradually decreased along the production cycle.

Significant linear correlations were observed between some water quality parameters, although with low correlation coefficients (Table 2). The pH was sig-

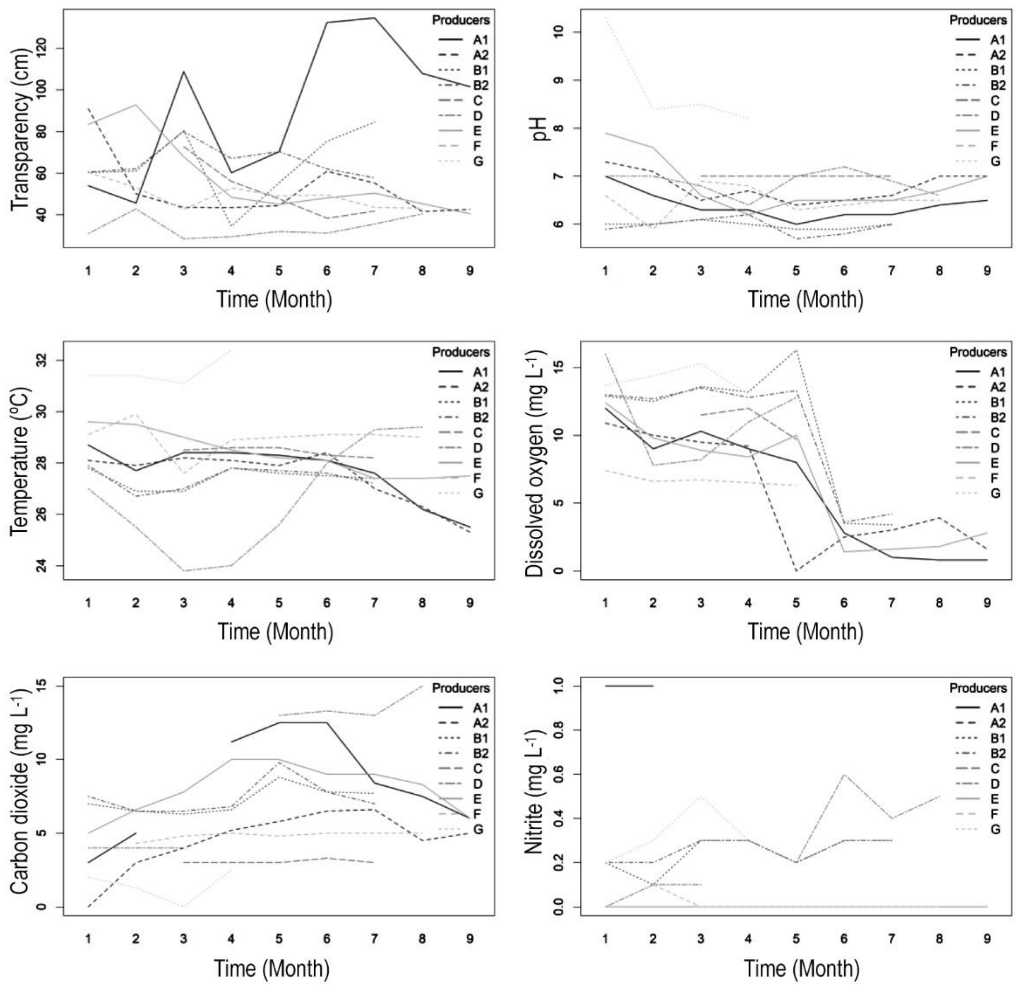

Figure 2. Time series of the dissolved oxygen, carbon dioxide, water transparency, pH, temperature, and nitrite for tambatinga (♀*Colossoma macropomum* × ♂*Piaractus brachypomus*) production in seasonal ponds.

nificantly correlated with all water quality parameters except ammonia. Likewise, dissolved oxygen was significantly correlated with all water quality parameters except ammonia and alkalinity. In contrast, ammonia was only significantly correlated with nitrite and alkalinity.

The occurrence of rainfall in the study region was high during the first four months of cultivation, becoming less frequent during the fifth month, and ceasing between the sixth and seventh month. Rainfall occurred between four and seven months, determining the duration of the production cycle at the different farms (Table 3).

Fish performance and mortality

Fish performance varied significantly among fishponds. During the initial grow-out phase (53 days of cultivation) , in general, the increase in fish weight was highest for the production units that received liming and fertilization, followed by those that received only fertilization, and was lowest for production units that received no preparation procedures ($P < 0.01$) (Table 4). The procedures of liming and fertilization were performed prior to fish stocking. A significant correlation between fish weight following 53 days of cultivation and water quality parameters was only found for pH (0.876; $P < 0.01$).

The weight variation and weight gain per month of the tambatinga during its production cycle in the monitored fishponds are presented in Figure 3, and the maximum and final weight and daily weight gain are presented in Table 4. Fish grew until approximately 150 to 200 days of cultivation (between the fifth and the sixth month), when they reached their maximum weight of 152 to 760 g.

This was followed by a period of weight loss, beginning after the last rainfall event in some farms, resulting in final weights between 135 and 549 g for a cultivation time between 90 and 271 days (Table 4).

Table 2. Pearson correlation coefficients for the relationships between water quality parameters during one production cycle of tambatinga (♀*Colossoma macropomum* × ♂*Piaractus brachypomus*) in seasonal ponds. T: temperature; WT: water transparency; DO: dissolved oxygen; A: ammonia; CD: carbon dioxide; Alk: alkalinity; N: nitrite. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

	T	WT	DO	pH	A	CD	Alk	N
Water transparency	0.04	-						
Dissolved oxygen	0.29*	0.29*	-					
pH	0.48***	-0.25*	0.26*	-				
Ammonia	-0.17	-0.01	0.10	-0.01	-			
Carbon dioxide	-0.21	0.47***	-0.28*	-0.47***	-0.08	-		
Alkalinity	0.19	0.46***	0.15	0.46***	0.45***	-0.06	-	
Nitrite	0.14	0.07	0.34*	0.07***	-0.25*	0.08	0.08	-

Table 3. Rainfall frequency during one production cycle of tambatinga (♀*Colossoma macropomum* × ♂*Piaractus brachypomus*) in seasonal ponds. NQ: not quantified. *Month following the end of the production cycle or monitoring. **Different letters indicate different farms, and different numbers indicate more than one production unit within a given farm.

Month	Monthly rainfall frequency (%) per farm					
	A	B	C	D	E	F
December	NQ	58.82	NQ	NQ	NQ	NQ
January	52.38	61.29	NQ	42.86	25.00	NQ
February	32.14	59.26	42.86	28.57	35.71	47.83
March	41.94	51.61	54.84	35.48	51.61	29.03
April	23.33	33.33	23.33	13.33	26.67	26.67
May	6.45	19.35	6.45	6.45	9.68	6.45
June	0.00	6.67	6.67	0.00	3.33	0.00
July	0.00	0.00	*	*	0.00	0.00
August	0.00	*	*	*	0.00	0.00
September	0.00	*	*	*	*	*
End of production cycle/monitoring**	September	June (B2**) and July (B1**)	June	June	August	August

The mean tambatinga daily weight gain until the animals reached their highest weight was 2.13 g. Except for farm D, where the fish were transferred to another pond located in the same farm that does not dry out, fish weight increased until 120 days of cultivation and then decreased, coinciding with the decrease in rainfall observed starting in the fifth month. Between 170 and 200 days of cultivation, weight gain became negative, indicating fish weight loss in most production units. In farm E, weight gain was again positive in July (seventh month), following the removal of 47 fish in June to decrease the stocking density. However, fish weight decreased again during the eighth month of cultivation.

The analysis of the correlations between fish weight variation along the production cycle and water quality parameters and time of cultivation revealed that the fish weight variation along the production cycle was significantly correlated ($P < 0.05$) with the time of cultivation (0.8412), dissolved oxygen (0.6977), carbon dioxide (0.5249), and nitrite (0.3057). However, the correlation coefficients were low for the correlations with carbon dioxide and nitrite (Table 5).

Multiple stepwise linear regression analysis, with fish weight as the dependent variable and the time of cultivation and water quality parameters as the independent variables, revealed that the fish weight variation was best explained by a model containing five variables (Table 6).

The accumulated fish mortality during the production cycle remained under 10% for most production units (Table 1). The fish mortality observed in production unit B2 was related to fish health problems caused by the protozoan ectoparasite *Piscinoodinium pillulare* (Schäperclaus, 1954) in the sixth month of cultivation. The mortality event lasted four days, with a total loss of 131 fish (48.5%). Necropsies were performed, and *P. pillulare* was

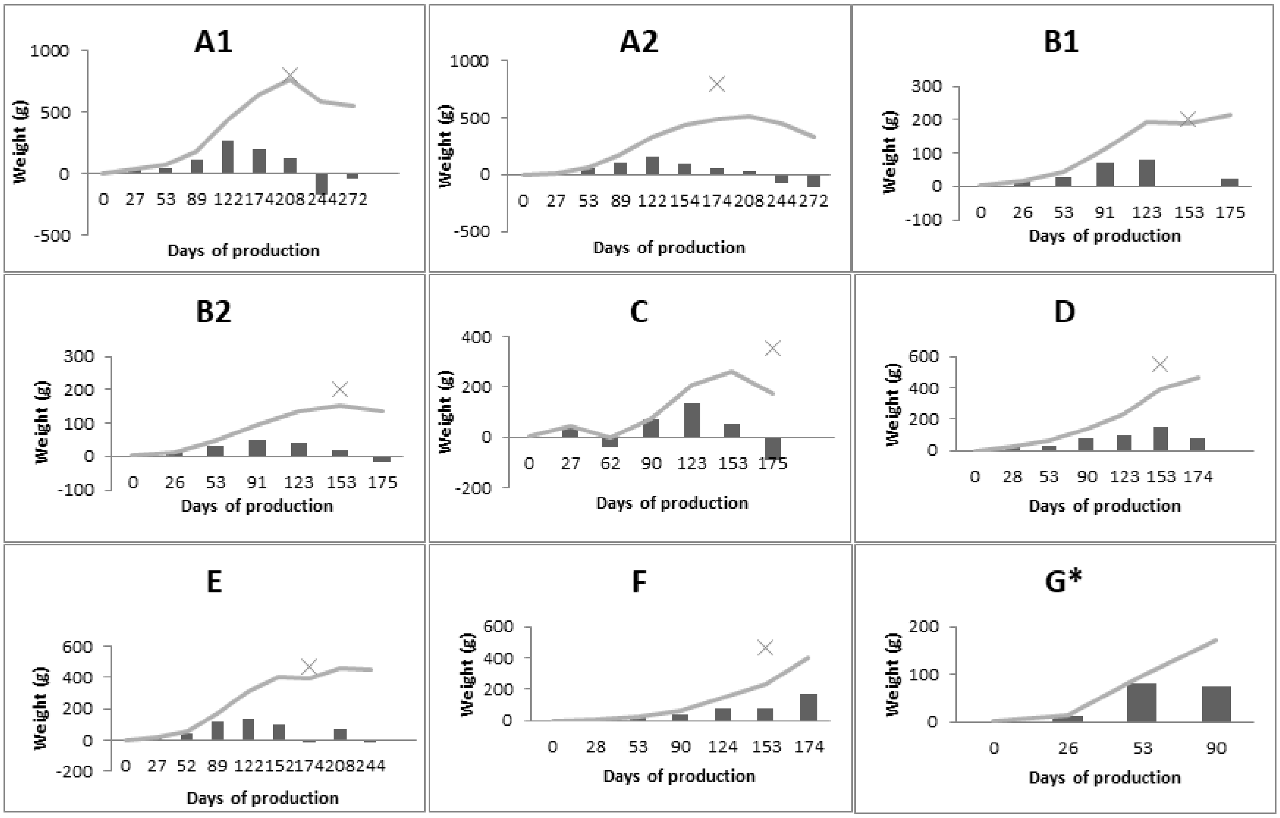

Figure 3. Weight growth curve (line) and weight gain (bars) of tambatinga (♀*Colossoma macropomum* x ♂*Piaractus brachypomus*) grown in seasonal ponds. The “x” indicates the last rainfall. A, B, C, D, E, F, G indicate the different farms, and different numbers indicate more than one production unit within a given farm. *Cultivation ended early due to problems with the production unit.

Table 4. Mean initial (at 53 days of cultivation), maximum and final fish weight, daily weight gain, time of cultivation, and fish pond preparation procedures performed. *Different letters in the same column indicate different farms, and different numbers indicate more than one production unit within a given farm. **Time between the beginning of the production cycle and the time when the animals reached the highest weight. ***Calculated for the period between the beginning of the production cycle and the time when the animals reached the highest weight. ****Production cycle ended early due to problems with the production unit. [ab]Means followed by different letters within the same column are significantly different according to Tukey’s test ($P < 0.05$).

Production unit*	Pond preparation		Initial weight (g)	Weight at 53 days (g)	Maximum weight (g)	Ideal period** (days)	Final weight (g)	Actual period (days)	Daily weight gain (g day^{-1})***
	Liming	Fertilization							
A1	Yes	Yes	1.5	96.3a	760	208	549	271	3.65
A2	Yes	Yes	1.5	66.7a	519	208	328	271	2.50
B1	Yes	Yes	1.5	64.8a	214	174	214	174	1.23
B2	No	Yes	1.5	59.3ab	152	153	135	174	0.99
C	No	Yes	1.5	57.14ab	261	153	170	174	1.70
D	No	Yes	1.5	46.5ab	465	173	465	173	2.69
E	No	Yes	1.5	43.4ab	463	208	449	244	2.23
F	No	No	1.5	42.7b	401	173	401	173	2.32
G****	No	No	1.5	27.5b	172	90	172	90	1.91

Table 5. Correlation between weight and water parameters of tambatinga (♀*Colossoma macropomum* x ♂*Piaractus brachypomus*) production in seasonal ponds. *P < 0.05; **P < 0.01; ***P < 0.001.

Dependent variable	Independent variable	Pearson's correlation coefficient	*P*-value
Weight	Temperature	-0.2380902	0.07722
	Period (month)	0.8412025	2.22e-16***
	Water transparency	0.2580406	0.05958
	Dissolved oxygen	-0.6977079	6.404e-09***
	pH	-0.1939196	0.1521
	Ammonia	-0.06622796	0.6375
	Carbon dioxide	0.524862	5.468e-05***
	Alkalinity	-0.04297589	0.7599
	Nitrite	-0.3057114	0.02601*

Table 6. Multiple regression model for weight and independent variables. R^2 = 0.7831; *P*-value = 6.299e-14. *P < 0.05; **P < 0.01; ***P < 0.001.

Dependent variable	Independent variable	*B*	*P*-value
Weight	Intercept	-346.45	0.062
	Period (month)	47.17	1.76 e-05***
	Water transparency	1.13	0.066
	Dissolved oxygen	-10.21	0.028*
	pH	39.86	0.067
	Carbon dioxide	21.660	0.002**

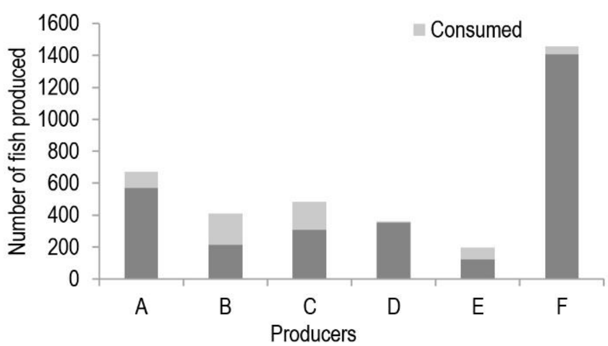

Figure 4. Amount of fish produced in the studied farms and fish consumption by the farmers.

identified according to Martins *et al.* (2015). No treatment was applied because mortality decreased (43, 39, 25, and 24) and completely ceased on the fourth day. Overall, mortality was concentrated in the first month of cultivation in all production units.

Fish consumption

Fish consumption by farmers and their families occurred in all farms monitored in the present study, corresponding to between 2 and 48% of the total production (Fig. 4). Regarding commercialization, all farmers were able to sell part or all their production to the local community, even if the production cycle was terminated when the fish was still very small.

Economic evaluation of the production

Considering the actual production period, fish farming resulted in losses for most farmers (Table 7). However, eight of the nine production units presented a positive net margin, showing that fish farming was economically unviable if the opportunity cost of labor was taken into account. B2 was the only farm that presented a negative net margin, which was due to the high mortality rate caused by the disease observed in the sixth cultivation month. When the ideal production period was considered (the period during which the production units exhibited their maximum production potential), five of the nine production units could have obtained profit from fish farming, even considering the farmers' labor as the opportunity cost of labor. In addition, the highest profit was obtained in farm F, which stocked the highest number of fish and therefore diluted the opportunity cost of labor.

The feed was the most expensive cost item in fish farming, representing 75 to 91% of the effective operational costs. Fish fry was the second most expensive item, representing between 6 and 22% of the production costs (Table 8).

Table 7. Overall summary of the cost of production of tambatinga (♀*Colossoma macropomum* x ♂*Piaractus brachypomus*) in seasonal ponds for two different harvest times. Actual period - total production cycle; Ideal period - estimated for a hypothetical scenario with harvest performed when the fish reached the highest weight. GI: gross income, TOC: total operational cost, TC: total production cost (including the opportunity cost of labor), NM: Net margin, the difference between GI and TOC, P: profit considering the difference between GI and TC. *Different letters indicate different farms, and different numbers indicate more than one production unit within a given farm. **Production was ended early due to problems in pond structure.

Production unit*	Production cost (US$)									
	Actual period					Ideal period				
	GI	TOC	TC	NM	*P*	GI	TOC	TC	NM	*P*
A1	388.08	209.03	473.01	179.05	-84.93	536.26	198.68	412.19	337.58	124.07
A2	288.61	200.09	463.10	88.51	-174.43	458.95	193.72	406.26	265.23	52.69
B1	138.88	87.91	270.37	50.97	-131.49	-	-	-	-	-
B2	42.37	82.32	264.77	-39.95	-222.40	-	-	-	-	-
C	193.77	141.95	272.96	51.82	-79.19	297.15	141.95	252.58	155.20	44.57
D	395.04	131.42	312.91	263.62	82.14	-	-	-	-	-
E	206.76	141.14	390.55	65.62	-183.80	213.01	122.42	336.90	90.60	-123.88
F	1379.72	545.10	724.65	834.62	655.08	-	-	-	-	-
G**	72.04	42.13	141.12	29.91	-69.08	-	-	-	-	-

Values are in US Dollars (US$ 1 = R$ 3.39)

Table 8. Percentage participation of each cost item on the effective operational cost of production of tambatinga (♀*Colossoma macropomum* × ♂*Piaractus brachypomus*) in seasonal ponds. *Different letters indicate different farms, and different numbers indicate more than one production unit within a given farm.

Production unit*	Participation in the effective operational cost (%)				
	Feed	Fish fry	Correctives	Fertilizers	Maintenance of machinery and equipment
A1	85.99	6.64	6.19	0.70	0.49
A2	81.95	10.06	6.71	0.75	0.53
B1	77.24	15.11	-	7.32	0.33
B2	75.37	16.41	-	7.87	0.35
C	82.09	16.40	0.77	0.55	0.20
D	86.29	12.81	-	0.69	0.21
E	91.00	8.80	-	-	0.20
F	82.49	17.33	-	-	0.18
G	75.68	22.73	-	0.84	0.76

The feed was the most expensive cost item in fish farming, representing 75 to 91% of the effective operational costs. The fish fry was the second most expensive item, representing between 6 and 22% of the production costs (Table 8).

DISCUSSION

Fish farm characteristics

The mean area of fish farms in the study region is within the recommended area for family fish farming (300 m²) because it allows the production of enough fish to meet the family demands and of surplus for commercialization and has lower construction costs (Gopalakrishnan & Coche, 1994; Carballo *et al.*, 2008). Larger cultivation structures can stock larger numbers of fish and, consequently, have higher production costs, which in many cases would not be suited to the financial capacity of the families. However, larger structures would enable higher production volumes and dilute the opportunity cost of labor, as discussed in section “Economic evaluation of the production”.

The use of livestock watering ponds for fish farming is common in many regions in Brazil (Garutti, 2003), allowing farmers to optimize the use of their production infrastructure. Considering that small bodies of water can have multiple uses in rural properties (Little *et al.*, 2006) and that production diversification is a characteristic of family agriculture (Buainain *et al*., 2003), the use of livestock watering ponds for multiple purposes on the farms reinforces the production diversification characteristic of family farms. However, this integration of the production space would be more efficient if fish farming was planned before the watering ponds were constructed, enabling the inclusion of the necessary technical requirements for fish farming, such as water entrance and exit and appropriate depth and slope. The high depth of the ponds studied results from the need to maintain the water in ponds for longer during the dry season, as previously reported for India by Kumar (1992). However, the high depth made the fish harvest for monthly biometric measurements and consumption by the farmer more difficult.

Although these technical deficiencies in pond construction do not prevent the development of fish farming in the studied region, they hinder fish production management and performance. For example, the construction of ponds for fish farming in soil with high drainage, together with the farmer's low resources and lack of input alternatives in the region for waterproofing the pond bottom, led farmer G to end production early in the third month. Fishpond E was built so that it received water from a dam reservoir with 6,000 m^2, thereby maintaining 1.5 m water depth during the dry season, but this water supply ceased during the dry season due to the insufficient slope. In the fish pond, C, the impossibility of completely draining the pond for its disinfection before fish stocking resulted in a high number of invasive fish (mainly *Geophagus* sp.), which competed with tambatinga for food and oxygen, have no commercial value and are not traditionally consumed by farmers as food. Therefore, planning of the production units so that they can be used for both fish farming and other activities is important.

Water quality and rainfall

Temperature and pH were stable during the production cycle and within the recommended values for fish production (Boyd & Lichtkoppler, 1979; Baldisseroto & Gomes, 2010). Only production unit G presented a higher mean pH than the remaining production units, but this pH was still within the recommended range. Because liming was performed when the ponds were still empty of water and before stocking, the water alkalinity level for each unit was not known. Production unit G, therefore, would not have required liming, which resulted in increased water pH and alkalinity. This was also the case with production units D, E, and F, which presented alkalinity within the indicated range for fish production even without liming. Two of three production units that received liming also presented alkalinity within the indicated range for fish farming.

Water transparency varied among the production units, initially due to the fertilization performed. In spite of variations, the overall water transparency remained within the recommended values for fish farming, being initially higher and decreasing along the production cycle. This change in transparency was expected for fish farming and probably explains the inclusion of water transparency in the regression model obtained for the fish weight variation (Table 6). Total ammonia and nitrite remained at adequate values for fish production even at the end of the production cycle when there was no more water renewal, and the overall concentrations of nitrogen compounds were higher (Boyd & Tucker, 1998; Faria *et al*., 2013; Moro *et al.*, 2013). The observed ammonia concentrations indicated that without water limitation, fish production could have been maintained for a longer period, even without water renewal.

Some production units presented high water carbon dioxide concentrations but within the recommended values for fish farming (Boyd & Tucker, 1998). The dissolved oxygen concentration was one of the limiting factors for fish performance, as it was lower than recommended during almost the entire production cycle, especially during the final months (Silva *et al*., 2007; Gomes *et al*., 2010; Faria *et al*., 2013; Moro *et al*., 2013). It reached critical levels several times, resulting in changes in fish behavior, with the fish rising to the surface in search of better oxygen concentrations at the water-air interface. This behavior is an adaptive mechanism called aquatic surface respiration (ASR) and is associated with the expansion of the lower lip, which funnels the thin surface layer of oxygen-rich water toward the gills (Val & Almeida-Val, 1995). However, no mortality was observed from water-quality problems, showing the resistance of this hybrid, similar to that of the parental tambaqui, to low dissolved oxygen concentrations (Silva *et al*., 2007; Gomes *et al*., 2010).

The correlations observed among the water quality parameters are characteristic of the water quality dynamics in fish farming environments (Boyd & Lichkoppler, 1979). The increase in nutrient input to the fishpond environment due to feeding supply results in increased phytoplankton populations through the production cycle and, consequently, in higher production of oxygen and carbon dioxide. This explains the correlations observed among water transparency and pH, carbon dioxide, and dissolved oxygen. Temperature, in turn, affects photosynthesis and respiration and, consequently, the dissolved oxygen level and pH. The ammonia concentration was not correlated with pH or dissolved oxygen, possibly due to the low variation in the ammonia concentrations during the production cycle; ammonia concentrations were therefore only correlated with nitrite and alkalinity. The correlation observed between pH and alkalinity is explained by the fact that alkalinity is an expression of the buffering capacity of water, and the correlation between pH and nitrite concentration is explained by ammonia nitrification, which decreases the pH. Ammonia nitrification also explained the significant correlation between ammonia and nitrite concentrations.

In fish farming in seasonal ponds, the production cycles are naturally shorter. Fish species that can reach adequate weight for commercialization during these shorter periods should be selected. The production cycle for roundfish is usually one year (Gomes *et al.*, 2010), and fish farming in seasonal ponds at the study region was only possible for six to seven months. However, this shorter period was sufficient for tambatinga to reach the necessary size for commercialization at the local community. Similar production cycle durations have been reported for family fish farming in seasonal ponds in Bangladesh, showing that shorter production cycles are not an impediment to fish farming in seasonal ponds in Brazil (Gupta, 2001; Roos *et al.*, 2002).

Fish performance

Liming and fertilization were associated with better animal performance during the first 53 days of cultivation, resulting in a significant correlation between weight and pH for this period. The liming of ponds for fish farming is performed with the aim of neutralizing pH, increasing alkalinity, and promoting biological productivity, thereby improving the water quality for fish production (Kungvankij & Chua, 1986). The aim of fertilization is to improve the natural fertility of ponds to allow the development of zooplankton (Karim *et al.*, 2011; Mischke, 2012), which are naturally consumed by tambaqui (Goulding & Carvalho, 1982; Silva *et al.*, 2003). The fish farms that received both procedures, therefore, exhibited better fish performance, reaching a mean fish weight of 67.61 g at the end of 53 days. This weight was higher than reported by Silva *et al.* (2007) for tambaqui grown for 60 days in fishponds that had received liming and fertilization, which reached a final weight of 46.47 ± 1.4 g. This reinforces the importance of these procedures to improve animal performance during this stage of cultivation and to optimize fish growth within limited production cycles due to water restrictions. Karim *et al.* (2011) studied the production of Nile tilapia (*Oreochromis niloticus*, Linnaeus, 1758) in Asia and concluded that to increase productivity in family fish farming, increasing the nutrient concentrations in fish ponds is more viable than increasing the stocking densities, which confirms the importance of this type of management.

The failure to adopt practices of pond preparation for fish farming is, in most cases, related to a lack of knowledge about fish farming (Karim *et al.*, 2011). The access to the necessary inputs for these procedures is not usually a limiting factor, as some of these inputs can be acquired or are already routinely used in family farms for breeding of other animals and small-scale agriculture.

The fish weight loss following the last rainfall in the region resulted from worsening of the water conditions (especially dissolved oxygen), which resulted from the impossibility of renewing the pond water. In addition, after the last rainfall, the water volume at the ponds began to decrease, resulting in higher number of fish per water volume, a higher stocking density, and critical oxygen levels, which may have also contributed to fish weight loss.

Regardless of the weight-gain variations among the different production units, the observed overall weight gain was higher than that reported by Izel & Melo (2004) (1.69 g d^{-1}), and Paula (2009) (1.25 g d^{-1}), showing the positive response of the animals to the studied production system. However, the overall weight gain was lower than that reported by Padilla (2000) (1.1-1.8 g d^{-1}), and Arbeláez-Rojas *et al.* (2002) (4.5 g d^{-1}), indicating that the management practices adopted can be improved to maximize the production potential of the species, even under water-deficit conditions.

Overall, the highest fish weights, between 401 and 760 g, were reached between 170 and 200 days of cultivation, when the last rains occurred in the region. This would be the ideal time for harvest. Until that time, the overall fish growth was within the expected values for the species (SEBRAE, 2013). However, most fish were not harvested at this time and lost weight, exhibiting lower weight at the end of the production cycle than expected for tambaqui grown in ponds without water deficit, which can reach from 1 kg in 270 days (Oliveira *et al.*, 2004) to 2 kg in 360 days (SEBRAE, 2013) from an initial weight of 1 g.

In India, De *et al.* (2012) observed that beginning cultivation with larger fish fry is a possible strategy to optimize the rainfall period in regions with water deficit or in ponds with low water retention capacity, resulting in higher final biomass. This could also be a possible strategy to optimize production in the studied production systems.

The strong correlation between fish weight and cultivation time was expected. The correlation between fish weight and dissolved oxygen, carbon dioxide, and nitrite concentrations reflected the importance of these parameters to the fish development. Dissolved oxygen concentrations outside the fish comfort zone decrease fish growth rates (Boyd & Lichtkoppler, 1979). The level of dissolved oxygen is usually more critical at the end of the production cycle due to the high fish biomass, which explains its correlation with fish weight. Similarly, carbon dioxide production increases with increasing fish biomass due to increased fish respiration rate.

Mortality

The fish mortality observed in the studied production units was within acceptable levels for fish production (Izel & Melo, 2004; EMBRAPA, 2006; SEBRAE, 2013). Higher mortality during the first month of cultivation was expected, as this is the stage when fish are more sensitive and when the highest mortalities naturally occur (Chagas *et al*., 2005; Gomes *et al.*, 2010).

High mortality was only observed in one production unit, and this was caused by parasitosis. The protozoan *P. pillulare* parasitizes fish gills and skin, causing velvet disease. The parasite's reproduction is favored by the poor water quality caused by high fish densities and excess organic matter (Martins *et al*., 2015). Martins *et al.* (2001) reported that hybrids such as tambacu suffer higher rates of parasitism by *P. pillulare* than pure species such as *Piaractus mesopotamicus* and *Colossoma macropomum*. In the present study, the velvet disease outbreak was associated with decreased or cessation of food consumption by fish seven days before the first day of mortality. Hyporexia is a classic indicator of health or water quality problems (Noga, 1996). In addition, biometric measurements were performed two days before the outbreak, which was an additional source of stress to the fish and may have contributed to decreased fish immunity, making the fish susceptible to the presence of the parasite in the environment.

Although the water quality was poor at the end of the production cycle, this did not cause tambatinga mortality in most production units, as tambatinga are quite resistant and adapted to regions with water deficit.

Fish consumption and commercialization

Fish consumption by farmers along the production cycle varied widely among the different production units but occurred for all units, confirming the importance of including fish farming in family agricultural systems as a way of introducing high-quality protein into the diets of the families. This is one of the most important contributions of family fish farming (Muir & Nugent, 1995).

Buainain *et al.* (2003) also observed variations in the degree of consumption between farms depending on the production system adopted and the level of capitalization of farmers. The authors observed that even among the farmers with the highest level of capitalization in southern Brazil, family consumption corresponded to almost 20% of the total fish farm production. In some areas of northern and northeastern Brazil, this percentage is considerably higher, as in some production units in this study, reflecting not only the precariousness of the means available to farmers but especially their isolation and distance from markets. In the studied region, fish farming is not the predominant production activity, and the fish that are traditionally consumed originate from fishing and, consequently, depending on seasonality. However, the inclusion of fish farming in the studied farms allowed fish consumption throughout the production cycle, even when the fish were still smaller than the commercial size.

Both fish consumption and fish commercialization at the local community occurred when the animals exhibited weight lower than the common market weight. Farmer C, for example, was able to sell his entire production when the fish had a mean weight of 170 g, showing the existence of a local market for fish under 200 g. This should be taken into account for this production system when planning harvests and sales along the production cycle because it allows farmers to gradually decrease fish density and generate income. The farmers who participated in the present study were able to sell part or all of their production to the local community, therefore contributing to the local food security.

Economic evaluation of production

Underwater deficit conditions, fish farming may be a profitable activity for family producers if correctly planned and managed. At the studied farms, the losses resulting from fish farming resulted from inadequate management, where the fish were harvested when exhibiting productivity loss. However, even in these cases, if the opportunity cost of labor was not taken into account, the fish production presented a positive net margin. If the farmers had performed the harvest at the ideal time, five of the nine production units would have obtained profit from the activity, even accounting for the opportunity cost of labor. This is a positive outcome for family producers, as, in addition to improving the family diet, fish farming may generate additional income and diversify income sources, increasing the economic security of farmers.

Regarding the production costs of a fish farm, the feed is the most expensive item (Martin *et al.*, 1995;

Scorvo-Filho *et al.*, 2004; Vera-Calderón & Ferreira, 2004; Andrade *et al.*, 2005). This was also observed in the present study. For *Pangasianodon hypophthalmus* (Sauvage, 1878) production in intensive, semi-intensive, and extensive systems, feed costs represented a high percentage of the total production costs but decreased with decreasing system intensity (75.8, 68.8, and 58.5%, respectively) (Ahmed *et al.*, 2010). In spite of the benefits of using industrial feeds, the cost of feed is still quite high for small producers (Tacon *et al.*, 2011; Ahmed & Toufique, 2014). In the studied region, however, the use of industrial feed is the most appropriate to fully exploit the growth potential of these fish, as fish performance and the production cycle are limited by water restrictions. Adopting systems that are more extensive would result in longer production cycles, which are not compatible with the local water availability. The cost of fish fry was the second-costliest item. The fish fry is usually an important item for production costs and deserves special attention from producers. Although the cost of fertilizers is low, this cost may be further decreased if the producer uses inputs obtained at the farm, such as organic fertilizers (Nhan *et al.*, 2006; Karim *et al.*, 2011).

Considering the economic evaluation of the studied farms, the importance of organizing the producers in associations for the purchase of inputs at lower prices should be highlighted. In addition, a positive factor for the studied group of fish farmers is the use of family labor because, in some cases, fish farming resulted in positive economic outcomes due to the lack of wage payment.

Karim *et al.* (2011) attributed differences in production and economic performance among small farmers producing tilapia under polyculture systems to differences in education, knowledge, and experience. These differences were also observed in the present study, together with the great scarcity of specialized technical assistance in the region. Technical assistance and rural extension programs may help increase farmer knowledge about fish farming and decrease these differences in the future. This is known to be one of the main bottlenecks for the development of fish farming in Brazil (Poli *et al.*, 2000; Ostrensky *et al.*, 2008; CNA, 2010). Increased knowledge about fish farming, together with the adoption of adequate production practices and production periods, is therefore expected to increase fish-farming efficiency and economic return to the families.

Evaluation of the participatory method

Participatory methods have been used in local communities and family farms to facilitate the development of research in collaboration with producers, making it more democratic (Nhan *et al.*, 2006; Karim *et al.*, 2011; De *et al.*, 2012). The training of farmers for the monitoring, which extended from farmer selection by the community to the training workshops, technical meetings, and monthly visits, was of great importance to the success of monitoring and exchange of experiences between farmers and researchers. In addition, the monthly workshops with the farmers participating in the study and with other local farmers resulted in increased social relations, culminating in the establishment of a local farmers association at the end of the study.

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