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A description of the culture of tambatinga (*Colossoma macropomum x Piaractus brachypomus*) in a South American tropical region and the interaction of farm size with value chains

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A R T I C L E I N F O

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A B S T R A C T

Understanding the economic efficiency of pond-based fish culture in tropical developing countries is essential for defining development programs. This study was designed to describe the aquaculture of tambatinga in various farm sizes that is being performed in a region close to the equator in Brazil called the midnorth. The major focus was on the economic performance and the relationship between different farm sizes and downstream value chains. We also describe the attractiveness of investments in small farms. A purposive sample of commercial tambatinga farms was taken. Sixteen farms were selected which encompassed a representative sample of progressively increasing production areas, ranging from 0.1 ha to 220 ha. Complete enterprise budgets were developed for each farm based on standard budgeting techniques, and indicators of financial feasibility were computed. The farming of tambatinga in the midnorth is performed in semi-intensive levee or watershed pond systems in farms of various levels of complexity and different production strategies. All farms perform a monophase cycle, stock small fingerlings (3 to 6 g) and feed fish with a commercial diet. Yield, net income, economic profit, net present value, internal rate of return and benefit/cost ratio were found to decrease as farm size increased. Payback period and break-even point increased as farm size increased. Small aquaculture farms ($\leq$ 1.5 ha) had a vertical business structure and presented a more effective economic performance. They are also attractive as family investments. This model of enterprise can boost rural economies and reduce poverty in developing countries. Large farms ($\geq$ 17 ha) were not economically feasible because they do not operate in the market and sell their production at lower prices. Increasing farm size should go hand in hand with improvements in technology to be feasible.

1. Introduction

Aquaculture in South America has increased in recent years (FAO, 2022). Most production is in Chile, Ecuador and Brazil. In the first two countries production is principally of marine species, mainly Atlantic salmon (Chile) and whiteleg shrimp (Ecuador), while Brazilian aquaculture is concentrated on freshwater fish (FAO, 2022). Production from fish culture increased by ~70% over the past 8 years in Brazil, reaching ~860,000 t in 2022 (PeixeBr, 2023). There is considerable potential for a much more significant expansion, considering the massive availability of water, its warm weather and its robust internal market (Valenti et al., 2021). Similar to the rest of the world, Brazilian

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aquaculture relies mainly on pond culture in small farms but some medium and large farms exist (Valenti et al., 2021). Most inland tropical fish culture in South America is performed in Brazil (FAO, 2022). Many species are farmed, among them the tambatinga.

Tambatinga is a cross bred fish between tambaqui (*Colossoma macropomum*) and pirapitinga (*Piaractus brachypomus*), two native species from the Amazonian region (Woynárovich and Van Anrooy, 2019). Farming this hybrid has been replacing the culture of pure tambaqui in some regions, mainly in the midnorth, a sub-region of the Brazilian Northeast region; national production reached 14,522 t in 2019 (FAO, 2021). Tambatinga are mainly produced in excavated ponds and, to a lesser extent, in net cages in reservoirs. They are characterized by their robustness, omnivore/filter feeding alimentary habit and the large harvest size that can be rapidly acquired when adequately managed (2 to 3 kg in one year of production). Tambatinga production is mainly carried out in monophasic or biphasic pond systems starting with 2–5 g fingerlings and harvesting at sizes of 0.8 kg to 2.3 kg. Farmers generally operate without aerators, resulting in a low production intensity (from 9 to 12 t/ha/yr); this is in contrast to tilapia that reach 30 to 60 t/ha/yr (Valenti et al., 2021). However, the higher sale value of tambatinga has enabled producers to compensate for this lower productivity. Producers are concentrated in the northern, midwestern and northeastern (midnorth) Brazil, which have small, medium and large farms (exceeding 400 ha) (Valenti et al., 2021). In the midnorth, however, tambatinga farms rarely reach 100 ha. This region is where about 40% of tambatinga farms have become concentrated in the past decade, representing nearly 2300 production units in 2017 (IBGE, 2023a).

In addition to the producers themselves, the aquaculture value chain involves an upstream supply chain (feed, seed and fertilizer suppliers) and a downstream supply chain (distributors and traders). These often generate more income and employment than the production itself (Beveridge et al., 2010; Gilson et al., 2023). The way farmers interact with these elements of the value chain may be important for improving profit and this interaction may depend on the farm size. Although this topic has been studied in other economic sectors, little information on this form of interaction is found in the scientific literature for domestic aquaculture supply chains (Belton et al., 2018; Hernandez et al., 2018). Some tambatinga farmers in the midnorth participate in fish downstream supply chains involving fish production and sales to retailers or final consumers to increase the margin of benefit from their activities; others do not participate. Therefore tambatinga culture in this region is an excellent model for studying the interaction of different farm sizes with their downstream supply chains in developing tropical countries. Our study was designed to describe the tambatinga aquaculture in various farm sizes that is performed in the midnorth, their economic performance and the relationship between farm size and the downstream value chain. We also describe the attractiveness of investments in small farms. Scale economy was not the primary focus of the present study, although some aspects are discussed; thus, we call "scale" the total area of ponds in each farm, not the intensity of production.

2. Materials and methods

The Brazilian states of Piaui and Maranhão represent a climatic, edaphic and vegetation transition area located between the semi-arid hinterlands and the equatorial Amazon. This region is officially called the midnorth, a sub-region of the northeast Brazilian region. The study took place in the north of Piauí and Maranhão, a tropical area close to the equator meridian (Fig. 1). Temperature is almost constant during the year, averaging 27.4 °C. Seasons are marked by ~4 months of rainy weather during the summer and ~8 months of dry weather during the winter.

A purposive sample (Sheppard, 2021) of commercial tambatinga farms was performed from July to November 2016. Sixteen farms were selected, which encompassed a representative sample of progressively increasing production areas of excavated ponds, ranging from 0.1 ha to 220 ha. These were respectively the minimum and maximum farm sizes encountered in the region. Farms were selected through a previous prospection with the assistance of the local rural technical service and other stakeholders of the tambatinga supply chain. We selected the most representative production systems of each farm size. The sampled farms represented about 0.7% of all the tambatinga farms in the midnorth. The

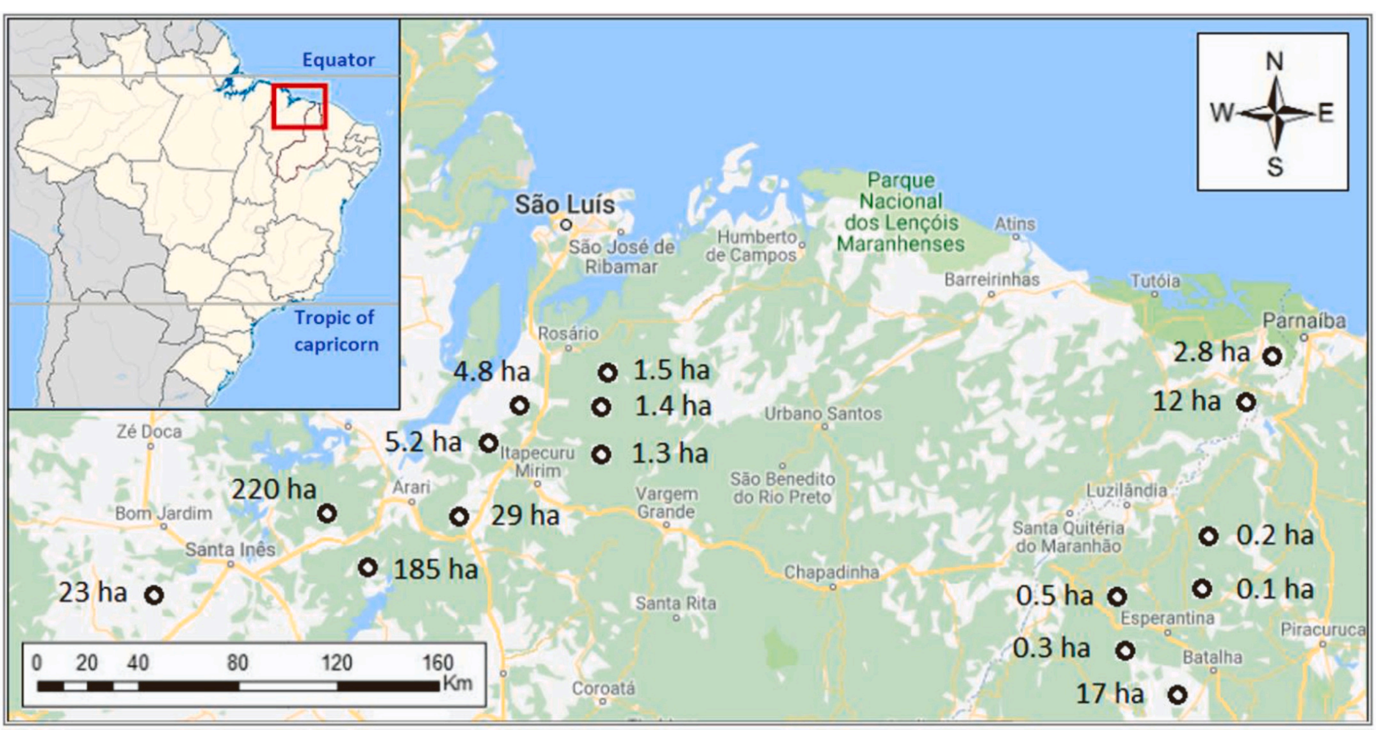

Fig. 1. Location of the farms studied in the Brazilian Northeast Region, showing the location and sizes of the farms studied.

farms operated semi-intensive production systems and were supplied by rainwater during summer and rivers or wells during winter. All used balanced commercial feed without fertilization.

Our survey was conducted through interviews with farm owners and employees, using questionnaires; these were conducted three times during the production cycle during personal visits to each of the 16 farms. Direct observations "*in loco*" and phone calls were also conducted to check and complete the information. The survey process revealed information on farm structure and operation, production practice and outcomes, investments (facilities and equipment), operating costs and trading (selling price and the expenses for selling). Monetary values were converted from Brazilian Reals (R$) to US dollars (US$), based on the average exchange rate for May 2017 (US$ 1.00 = R$ 3.22).

Complete enterprise budgets were developed for each farm based on standard budgeting techniques (Engle, 2010). Copies of complete budgets are available on request from the corresponding author. Based on these budgets we developed estimates of annual costs for producing food-size tambatinga and the respective returns obtained. We performed a cost-return analysis and computed traditional indicators of neo-classical economics, as described by Shang (1990) and Engle (2010). Cost-return analysis is the basic method for evaluating the economic performance of commercial aquaculture operations (Shang, 1990).

The expenses considered were the initial investments for the construction of facilities (ponds, storage shed, housekeeper's house, office, wells), the purchase of equipment, and the total cost of production (which was the sum of the variable and fixed costs). Variable costs were the acquisition and freight of fingerlings, commercial feed, calcium carbonate, temporary labor, fuel, taxes, electric power, telephone, test reagents, and other general expenses. Fixed costs were salaried labor, maintenance of equipment and facilities, farmer registration fee, depreciation, and opportunity costs (remuneration on the invested capital of the farmer and of the land). Depreciation was calculated by the linear method, according to Engle (2010).

The farms studied exhibited various methods of selling the fish produced, which resulted in different supply chain structures. The small farms (0.1 to 1.5 ha), except the 0.3 ha and the 1.5 ha farms, showed vertical integration, i.e., they were involved in downstream value chains from fish production to sales (in markets, at farm gates or directly at consumers' homes). The farms sized 0.3 and 1.5 ha, and all the larger farms, were selling fish to intermediary buyers; these sold them to supermarkets or wholesale markets. Gross revenues were obtained by multiplying the production by the unitary sale price obtained by each farm in their relevant supply chain. An average of the production in three subsequent years was used to estimate yield to cover possible fluctuations. Net revenue and economic profit respectively were obtained by subtracting the operating cost and total production cost from the gross revenue. We assumed that the inflation of production costs would be compensated by inflation in the prices obtained for the products sold.

The financial feasibility of each farm was determined through the use of traditional indicators of neoclassical economics, according to o Engle (2010), as shown below:

1. **Gross Revenue** (GR), which is a synonym for total revenue or total sales, was obtained by the yield (Y) x unit sales price (SP).

GR = Y x SP

2. **Total Production Cost** (TPC), which corresponds to the sum of fixed costs (FC) and variable costs (VC).

TPC = FC + VC

3. **Total Operating Cost** (TOC), which is the sum of operating costs (OC) and asset depreciation (D).

TOC = OC + D

4. **Net Income** (NI), which is the gross revenue (GR) minus the total operating cost (TOC).

NI = GR - TOC

5. **Economic Profit** (EP), which corresponds to gross revenue (GR) minus the total production cost (TPC).

EP = GR - TPC

6. **Net Present Value** (NPV), which is the present value of a series of future revenues for a period, discounted using the interest rate, subtracted from net investment. NPV is used to determine how much money an investment will generate compared with the cost adjusted for the time value of money. The interest rate was fixed at 8.5%, which was the basic interest rate at the time of our study (Brazilian government basic interest rate "SELIC" in 2017) with a computed period of 20 years.

$$NPV = \sum_{i=0}^{n} \frac{Bi - Ci}{(1+r)^i}$$

in which:
B_i = total benefit (or revenue) of year i;
C_i = total cost of year i (capital + operating costs);
r = discount rate;
n = number of years in operation (−0, 1, 2,…, n);
i = the i^{th} year.

7. **Internal Rate of Return** (IRR), which is a metric used in financial analysis to estimate the profitability of potential investments. IRR is a discount rate that makes the net present value (NPV) of all cash flows equal to zero in a discounted cash flow analysis.

$$0 = NPV = \sum_{t=0}^{n} \frac{C_t}{(1+IRR)^t} - C_0$$

in which:
C_t = net cash inflow during the period t;
C_0 = total initial investment costs;
IRR = internal rate of return;
t = number of time periods.

8. **Return on Investment** (RoI), which is the ratio between annual Net Income (NI) and Initial Investment (II). i.e., the income generated per unit of capital invested.

$$RoI = \frac{NI}{II} \times 100$$

9. **Benefit-Cost Ratio** (B/C), which is the discounted value of incremental benefits divided by the discounted value of incremental costs.

$$B \Big/ C = \frac{\sum_{i=0}^{n} \frac{Yi}{(1+r)^2}}{\sum_{i=0}^{n} \frac{Ki}{(1+r)^2}}$$

in which:
Y_i = net annual benefit of year i = $B_i - O_i$;
B_i = total benefit (or revenue) of year i;
O_i = operating cost of year i;
K_i = capital outlay for assets of year i (initial investments +

reinvestments);
r = discount rate;
n = number of years in operation.

10. **Payback Period** (PP), defined as the number of years required for the farm to recover the initial capital invested in the project.

$$\sum_{i=0}^{j} NCF_i = 0$$

in which:
j = PP in years;
NCF_i = annual net cash flow of year i;
i = 0, 1, 2, …j…, n.

11. **Break-Even Point** (BEP), which is the amount of sales (as a percentage) necessary to make the economic profit zero. This was calculated by dividing the fixed costs (FC) by the unit sales price (SP) minus the unit variable cost (UVC).

$$BEP = FC / (SP - UVC)$$

As there was a wide range of farm sizes, comparisons of their performance were made by dividing the annual income, economic profit and net present values for each farm by the yield of fish produced. Results from each farm studied were presented in vertical bar diagrams and scatter graphics. Farm areas ranged from 0.1 to 220 ha and showed asymmetric distribution. Thus, the logarithm (log_{10}) of farm size was presented on the X-axis in scatter graphics and was used in the regression analyses. Second-degree polynomial and linear regressions were used to determine relationships between farm size and various economic indicators and farm features. For some analyses, the farmers were grouped by size as follows: small farms (0.1 - 1.5 ha), medium farms (2.8 - 12 ha) and large farms (17 - 220 ha). These size groups reflected the typical conditions found in the midnorth region.

Farmers that operate in the supply chain after production (downstream supply chain) sell the fish for a higher value but have additional investment and operational expenses. To assess the effect of participation of farmers in this trade we simulated a scenario in which we subtracted the expenses of trading and computed the gross income assuming that all farmers would send their fish to middlemen for an average value of US$1.55/kg. We also computed the indicators of financial feasibility for this scenario.

3. Results

3.1. Farm design and production characteristics

Farm features, culture management and production of all farms studied are presented in Table 1. Average pond size ranged from 0.12 ha to 3.6 ha and was directly related to total farm size (Fig. 2 A). The average pond size in the two largest farms was ~3 ha, yet half of the ponds were more than 8 ha and the largest ponds reached 29 and 48 ha in the 220 and 185 ha farms, respectively. Levee, embankment, excavated and watershed ponds were being used. Canals, allowing independent filling and draining procedures, were only recorded in five of the sixteen farms studied; no relationship with farm size was observed.

Farming strategies were quite variable (Table 1). Lime was applied in most of the farms with a large variation in the quantity used (from 0.06 to 1.5 t/ha/yr) without any clear pattern related to farm size. All farms performed monophasic culture, stocking fingerlings of 3 to 6 g. The stocking densities ranged from 0.4 to 1.9 fingerlings/m^2, with a decreasing trend as farm size increased. The 2.8 and 12 ha farms used aerators with a total capacity of 4.4 and 2.7 HP/ha respectively. The 185 ha farm was also equipped with a few aerators for emergency purposes, which accounted for 0.1 HP/ha. Fish were fed one to five times daily at the beginning of the production cycle and once or twice a day at the final growth stage. Feeding frequency did not show any general tendency as farm size increased. Nevertheless, most of the medium size farms fed their fish more frequently (from 2 to 4 times/day) than small and large farms (1 to 3 times/day). Average fish weights at harvest lay between 0.5 and 1.6 kg. This meant that the average fish biomass varied from 0.4 to 1.7 kg/m^2 at harvest with a slight tendency to fall as farm size increased. In contrast, yield decreased markedly from ~17 t/ha/yr to ~3 t/ha/yr as farm size increased (Fig. 2B). The period between two production cycles, defined as idle or "down" time, represents the unproductive period between two crops when sales and pond management activities are taking place. Idle time increased with pond size, ranging from 10 days for the 0.18 ha pond to 150 days for the 25 ha pond (Fig. 2C).

The crude protein levels of the fish feeds used in each farm studied at the various fish development stages (chosenchosen according to the fish weight) varied among farms (Fig. 3). Feed conversion ratios (FCR) fluctuated from 1.1 to 1.8 (Fig. 4A) and the average crude protein content of the fish feeds used ranged from 28.3% to 33.7% (Fig. 4B). No pattern was found as farm size increased.

Table 1
General physical, culture management and yield characteristics of all farms studied. Farm size represents the total area of pond surfaces. Feeding frequency is shown in the weighted mean throughout the entire culture period.

Farm size (ha)	Average pond size (ha)	Water inlet and outlet canals	Lime use (t/ha/yr)	Stocking density (fingerlings/m^2)	Fish density at harvest (kg/m^2/crop)	Feeding frequency (times/day)	Grow-out phase (months)	Harvested mean weight (kg)	Yield (t/ha/yr)	Feed conversion ratio (FCR)
0.1	0.12	No	-	1.88	1.69	1-3	6.0	0.9	13.3	1.3
0.2	0.24	No	-	1.88	0.94	1	6.0	0.5	16.7	1.6
0.3	0.15	No	-	1.66	0.83	1-3	6.0	0.5	13.3	1.7
0.5	0.12	No	0.31	1.63	1.47	1	9.0	0.9	12.3	1.7
1.3	0.46	No	0.63	0.59	0.41	1	4.0	0.7	9.4	1.5
1.4	0.13	No	0.14	0.71	0.71	1-3	6.0	1.0	10.1	1.4
1.5	0.26	No	1.50	0.70	0.70	3-4	6.3	1.0	10.7	1.1
2.8	0.23	Yes	-	0.91	1.00	2-4	7.0	1.1	16.3	1.4
4.8	0.29	No	0.33	0.84	1.05	2-4	8.0	1.3	13.2	1.5
5.2	0.44	Yes	1.00	0.50	0.55	3-4	6.0	1.1	6.2	1.3
12	1.53	Yes	1.04	0.97	1.06	1-3	7.0	1.1	10.0	1.6
17	0.26	Yes	0.08	1.00	1.10	1	7.0	1.1	10.0	1.8
23	1.00	No	0.07	0.47	0.72	1	8.0	1.6	6.5	1.8
29	0.45	Yes	0.06	0.76	1.14	1-3	8.0	1.5	6.8	1.3
185	3.60	No	-	0.40	0.60	1	8.0	1.5	2.8	1.6
220	2.70	No	0.39	0.60	0.90	1	8.0	1.5	2.6	1.4

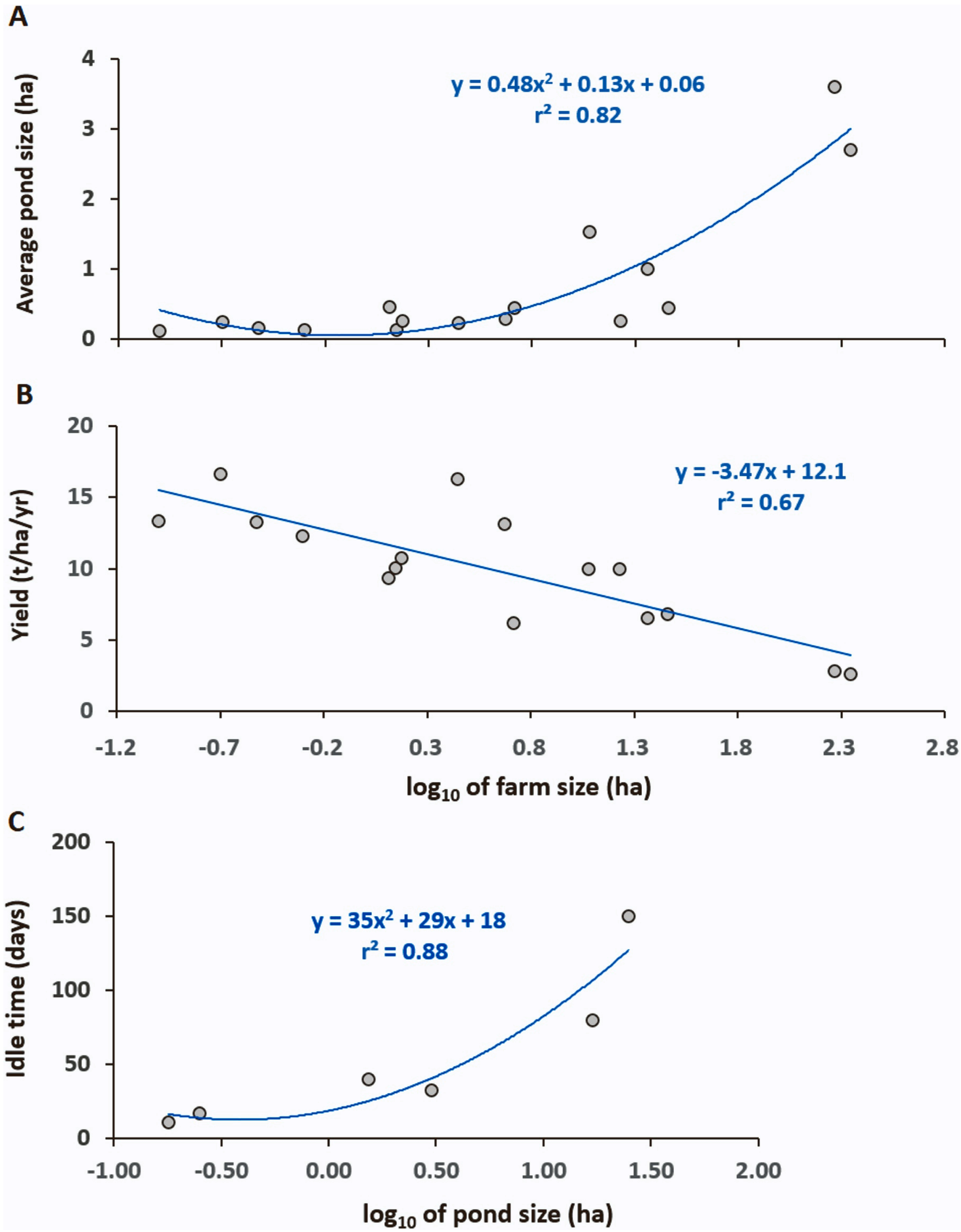

Fig. 2. Average pond size (A) and yield (B) as a function of farm size (ha) in log10, and Idle time (C) in 6 ponds, defined as the unproductive period between two production cycles, as a function of pond size (ha) in log10.

3.2. Investment and operating costs of fish production

Investment costs per unit of fish produced varied from US$ 848/t (1.5 ha farm) to US$ 2.408/t (23 ha farm) (Fig. 5A, data provided in Table 2). Vertically integrated farms under the simulated scenario, selling to intermediaries, are marked in red, while the other farms are indicated in black. Total investment was US$ 1704/t in the 0.1 ha farm, but drastically decreased to US$ 921/t in the 0.2 ha farm, and sharply increased to a peak of US$ 2.408/t in the 23 ha farm, remaining high in larger farms. The main components of investment were pond construction and other farm facilities, which exclude equipment and veihicles (Fig. 5A). Pond construction was 37 to 69% of the total investment, while other farm facilities were 9 to 35%. Farm facilities consisted simply of ponds, water pumping and pipework in small farms but in farms above 1.5 ha included a storage building, electrical wiring and wells, an office and a caretaker's house. The cost of land per unit of fish produced varied more than 3-fold, being lowest in the 0.2 ha farm (US$ 112/t) and highest in the 29 ha farm (US$ 376/t).

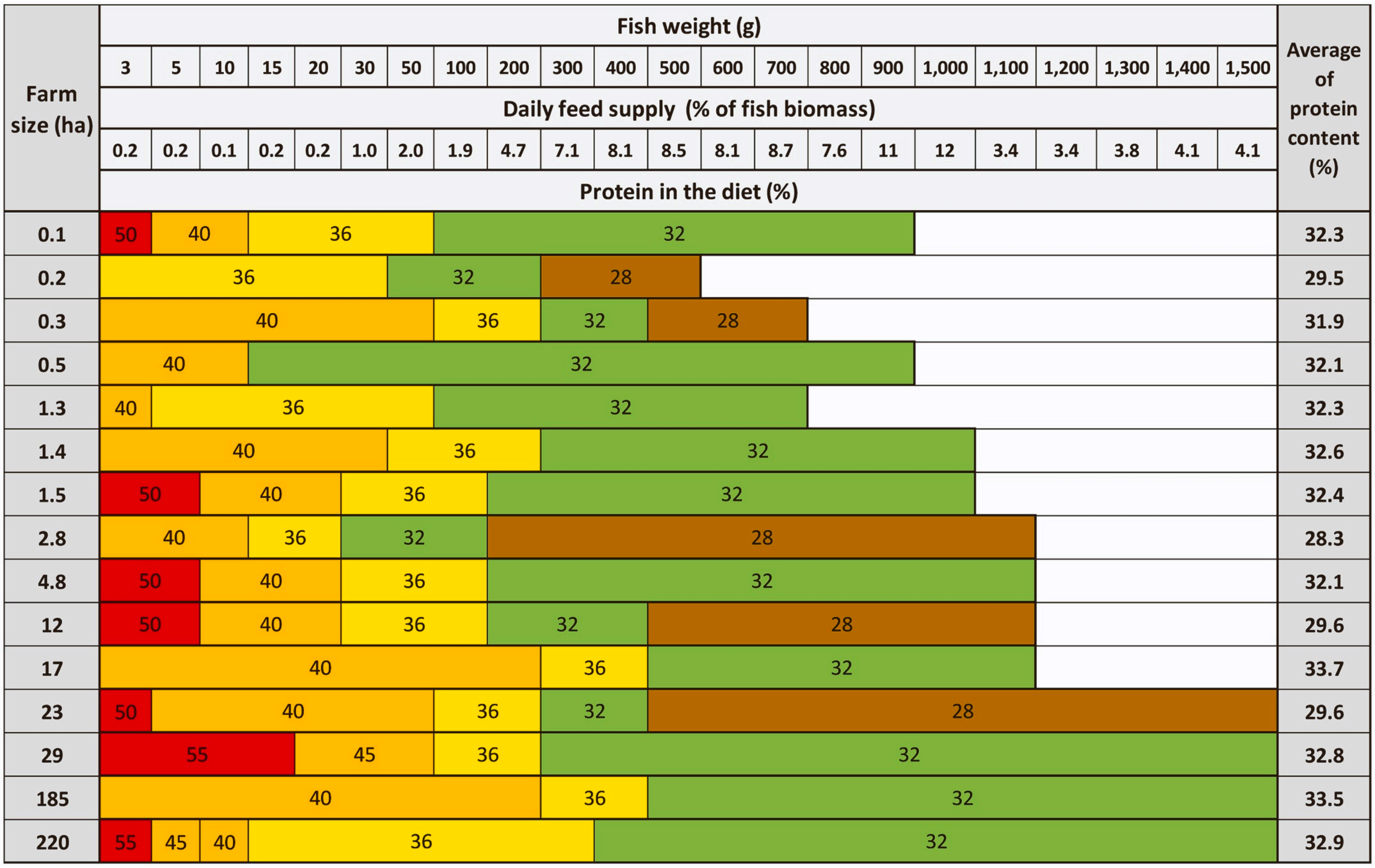

Fig. 3. Levels of crude protein (numbers inside bars) in feeds and the feeding rate as a percentage of biomass used in each farm studied during the culture period, according to tambatinga growth. The color of the bars represents the different levels of feed protein content: red bars = 50–55%; orange bars = 40–45%; yellow bars = 36%; green bars = 32%; brown bars = 28%. The data for the average protein content in the extreme right hand column is the weighted average of the feed protein content as a function of the feeding rate.

Vehicles in small farms were used only to trade production. The acquisition of a motorbike and trailer, used exclusively for farm management (and not for selling fish), began with the 4.8 ha farm, which was valued at US$ 49/t. As the farm size increased to 12 ha and beyond, the cost of vehicles rose due to the addition of pickups, trucks, tractors, and boats. By the time the farm expanded to 220 ha, the vehicle cost reached US$ 305/t.

Equipment mainly consisted of nets, scales, water tanks, buckets, wheelbarrows and, in larger farms, feeding machines and aerators. Equipment costs represent only a small part of the total investment, and its proportion within the investment cost tends to decrease as farm size increases.

Total operating costs per tonne of fish produced are shown in Fig. 5B (data provided in Table 3); vertically integrated farms under the simulated scenario that are selling to intermediaries, are marked in red, while the other farms are indicated in black. Total operating costs varied from US$ 872 (1.5 ha farm) to US$ 1483 (185 ha farm). Total operating costs were lower in farms from 1.4 to 12 ha. Feed represented 54% to 76% of the total operating costs. Feed costs were determined by the feed protein level (FPL) choice, the unit feed purchase price and the feed conversion ratio (FCR). The FPL and FCR showed a random variation among the farms studied (Figs. 3 and 4). The unit feed cost of fish produced varied from US$ 652 in the 1.5 ha farm to 1077/t in the 0.3 ha farm; the feed purchase price (based on feeds with 32% protein content) decreased slightly as farm size increased (Fig. 4 C). Labor was the second most expensive factor of production (Fig. 5B). The 0.2 ha farm spent US$ 200/t on labor but this figure gradually decreased to US$ 113/t in the 1.5 ha farm (Table 3 and Fig. 5 C). In the three larger farms, labor costs were high, with a peak of US$ 412/t in the 185 ha farm. Energy costs in tambatinga farms include electricity for pumping water and vehicle fuel. In large farms electricity was used for complementary facilities and/or some emergency aerators and automatic feeders. Energy costs (Table 3) decreased with farm expansion from US$ 61/t in the 0.1 ha farm to US$ 19/t in the 4.8 ha farm but increased thereafter. A peak was observed in the 185 ha farm (US$ 179/t). The other operating costs consisted of lime, telephone, bags, taxes and the environmental license fee, which varied from US$ 0.2/t to US$ 33/t in the studied farms and did not show any pattern related to farm size.

Labor diversification increased with farm size (Fig. 5C). Small farms rely exclusively on day-labor, with pay varying from US$ 1.5/h for maintenance to US$ 4.6/h for harvesting activities. Feeding is achieved by family members who do not receive monetary benefit; therefore a value has been calculated based on the cost of harvesting activities by day labor. From the 2.8 ha sized farm onwards, full-time labor is hired (44 h/week), which results in an increase of 42% in labor costs because of the social benefits paid by the farm. Feeding staff are the first fixed labor to be hired as farm size increases, with an average monthly wage of US$ 275 per person. Then, with farm size expansion, farms employ a night guard (US$ 319/t), a supervisor (US$ 1299/t), a driver (US$ 395/t), a secretary (US$ 396/t), a housekeeper (US$ 247/t) and an accountant (US$ 489/t).

3.3. Downstream value chain

Apart from the 0.3 and 1.5 ha farms, all the small farms were involved in various ways in the fish marketing value chain. In the 0.1 ha farm, sales occur at the farm gate, where clients buy fish valued at US$ 2.50/kg (Fig. 6; 1). In the 0.2 and the 0.5 ha farms, the owners' families

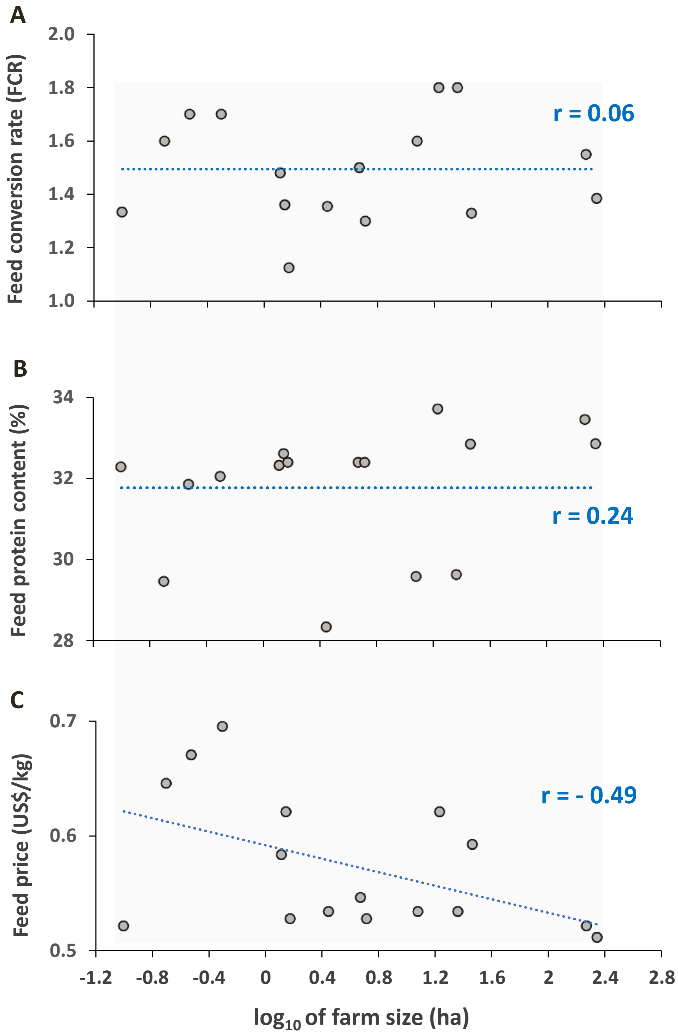

Fig. 4. Feed conversion rate (A), average feed protein content in the diets during a whole production cycle (B), and mean of 32% protein feed price (C) at the various farms studied. Farms are shown in the x-axis by farm size (ha) as log10. r = Pearson correlation coefficient.

transport fish using a motorbike or a car equipped with trailers to sell them directly to consumers at their homes for US$3.10/kg (Fig. 6; 2). In the 1.3 ha farm, the owner's family also transports fish by motorbike and trailer and sells them in a farmers market for US$ 3.10/kg (Fig. 6; 3). In the 1.4 ha farm, the owner's family transport their fish to the local farmers market where they sell them to traders at US$2.50/kg (Fig. 6; 4); these intermediaries resell the fish at their stalls for US$ 3.10/kg to the end consumers. The 0.3 ha farm and all the other farms sized from 1.5 ha and above sell their fish to middlemen for about US$ 1.63/kg (US $ 1.55/kg for fish with harvest weights below 1 kg and about US$ 1.70/kg for those above 1 kg (Fig. 6; 5)). The complete downstream value chain of tambatinga in the midnorth was described in detail by Gilson et al. (2023).

Farmers' investment needs for selling directly to consumers or market sellers generally declined with increasing farm size (Table 2). The 0.2 ha farm had the highest relative cost, which was up to 75% of its fish production cost. This proportion decreased as farms expanded: 70% for 0.5 ha, 19% for 1.3 ha, and a mere 17% for 1.4 ha. In contrast, the smallest 0.1 ha farm had zero additional costs, selling directly on-site (Table 2).

The most important item in investment is the vehicles, which may be motorbikes with trailers or cars (Fig. 6). The additional operational costs for farmers working in the supply chain, mainly composed of labor and energy, were generally lower than 20% of the operating costs for production. However, it reached almost 100% in the 1.3 ha farm mainly because of the labor required for market selling (Table 3).

3.4. Indicators of financial feasibility

We observed a clear linear relationship among all the indicators of financial feasibility and the farm size (Figs. 7 and 8). Net income, economic profit, net present value, internal rate of return, return on investment, and benefit-cost ratio decreased as farm size increased, while break-even point and payback period increased with farm size. All farms have positive net income, but the 0.3 ha farm and farms higher than 12 ha were unprofitable. Participation in a marketing value chain (vertical structure), which occurs in most of the small tambatinga farms, provides them with the best economic results (Table 4; Figs. 7 and 8). The average economic indicators of those farms that were involved in the fish supply chain (the 0.1, 0.2, 0.5, 1.3 and 1.4 ha farms) achieved a net income of US$ 1200 /t, an economic profit of US$ 972 /t, a net present value of US$ 8338/t, an internal rate of return of 36%, a return on investment of 77%, a benefit-cost ratio of 4.9, a break-even point of 22%, and a payback period of 3.1 years. Particularly high scores were achieved by the 0.2 and 0.5 ha farms which were involved in selling fish directly to consumers' houses. Among the farms not involved with the downstream value chain, only those from 1.5 to 12 ha were profitable, and profitability decreased as farm size increased (Table 4).

However, when we simulated the trade of production for a middleman, the results of small farms were lower or similar to those obtained for the middle size farms (Figs. 7 and 8). Farms from 1.3 to 12 ha, and the 0.2 ha farm, showed positive economic indicators (Table 4; Figs. 7 and 8) with the best results being obtained by the 1.5 ha farm. On average, these farms made an income of US$ 484/t, an economic profit of US$ 312/t, a net present value of US$ 2367/t, an internal rate of return of 20%, a return on investment of 47%, a benefit cost ratio of 2.20 and a payback period of 5.4 years. The break-even point was low, at 45%. The rest of the farms, smaller or larger than the range of 1.3 to 12 ha, had lower average income (US$ 184/t), low returns on investment (11%) and low internal rate of return (4%), and showed negative results in the indicators of economic profit (US$ −78/t), net present value (US$ −1206/t) and benefit cost ratio (−0.62). The pay-back period for smaller farms lay between 3.4 and 14 years, while that of the larger farms lay between 12 and 25 years. The break-even point averaged at 123%.

4. Discussion

This study revealed that the culture of tambatinga in the midnorth is performed in semi-intensive earthen pond systems in farms of different sizes and levels of complexity. Pond size and structure are diverse; most have no independent water inlet and outlet. All farms perform a monophase cycle, stock small fingerlings, and feed fish with a commercial diet 2 to 5 times daily. This panorama is similar to that observed in other regions for tambaqui (cf. Valenti et al., 2021), a major native freshwater fish produced in South America and a parental species of tambatinga. Therefore, tambatinga culture may be used as a model to understand the features of the culture of round fish (genus *Colossoma*, *Piaractus* and their hybrids) performed in tropical areas.

Investment and operating costs per tonne of fish produced were slightly lower in the medium-sized farms. This suggests an economy of scale effect from small to medium farms that turns into a diseconomy of scale as the farm size increases from medium to large. Economies of scale are widely recognized but diseconomies can also emerge because efficient management and business coordination become more difficult as the enterprise grows (Engle, 2010). When businesses expand beyond an optimal size, costs may rise disproportionately with the increase in farm productivity, mainly because investment in technology is neglected. In midnorth tambatinga culture, farm design, production

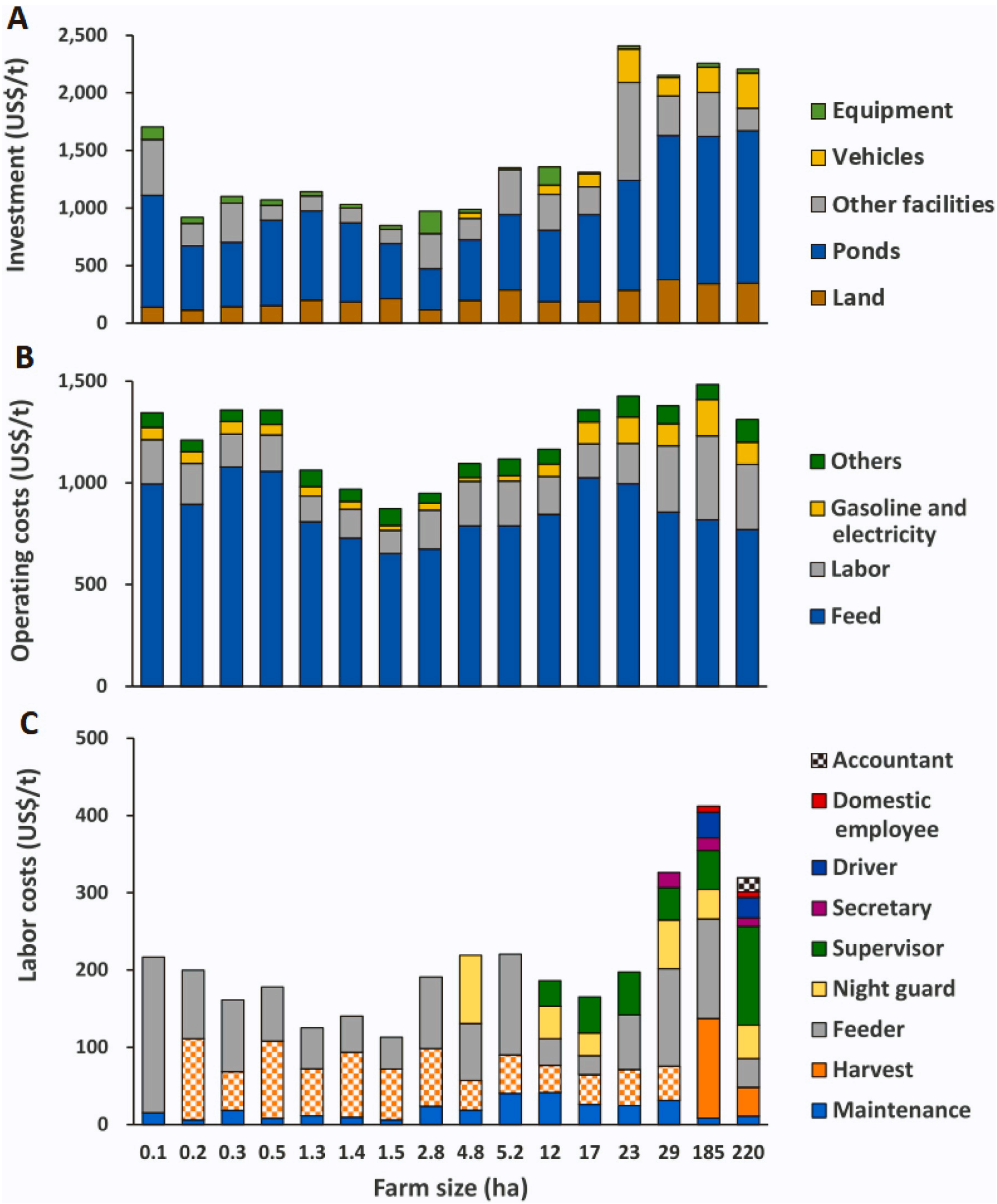

Fig. 5. Investment (A), operating costs (B) and labor costs (C) expressed in US$ per tonne of fish produced. Job position at labor costs (C) is represented in color code with checkerboard pattern for day-labor and full-color for fixed labor.

management and the level of technology did not improve in large farms. These include several large watershed ponds, which impairs better management and enlarges idle time, reducing annual productivity. In addition, the organizational and administrative complexity necessary for large farms increases labor costs with low effects on production efficiency.

The greatest investment item observed in the present study was pond construction in all farms. Similar results were obtained in former studies simulating farms at different scales in South America (e.g., Rodrigues et al., 2019; Dantas et al., 2022). These findings are normal in levee pond-based aquaculture (Engle, 2010). The present study demonstrated that this phenomenon occurs even in cheap watershed ponds. A consistent decrease in pond-related investments was observed as farm size increased. It falls from US$ 15000/ha for the 0.1 ha farm to US$ 2500/ha for the 220 ha farm. This reduction is mainly due to the increase in pond dimension, rather than to the rise in scale efficiency. Large tambatinga farms are based on large levees or watershed ponds. As the pond area expands, the construction effort per area unit reduces (Muir and Lombardi, 2010). This is primarily attributed to the diminishing ratio of the pond's perimeter to its overall surface area. The labor involved in shaping the boundaries of levee ponds often exceeds the challenges of mere excavation, making larger ponds more cost-effective. In watershed ponds, pond area is not directly proportional to the dam construction, which is the major cost in building these ponds.

Table 2
Value of each item of the investment in US$ per tonne of fish produced annually for each farm (shown in black). The investment costs of vertically integrated farms in the simulated scenario[1] is shown in red[1].

Farm (ha)	Land (US$/t)	Pond (US$/t)	Vehicles (US$/t)	Equipment (US$/t)	Other facilities (US$/t)	Total investment (US$/t)
0.1	140	970	-	109	485	1,704
0.1	140	970	-	109	485	1,704
0.2	112	559	660	90	194	1,615
0.2	112	559	-	56	194	921
0.3	142	559	-	60	341	1,102
0.5	151	743	722	70	129	1,815
0.5	151	743	-	48	129	1,071
1.3	199	776	207	50	129	1,361
1.3	199	776	-	38	129	1,143
1.4	185	685	171	33	129	1,203
1.4	185	685	-	33	129	1,032
1.5	212	480	-	34	122	848
2.8	114	359	-	195	304	972
4.8	198	527	49	29	184	987
5.2	288	654	-	16	392	1,350
12	186	621	80	157	311	1,355
17	186	757	116	11	241	1,311
23	286	952	293	26	851	2,408
29	376	1,253	161	20	344	2,153
185	343	1,278	221	33	382	2,257
220	347	1,324	305	36	196	2,207

[1]In which these farms would be selling all their production to intermediaries; it includes the cost of vehicles and equipment necessary for commercializing the yield. Data is only shown in black for the 0.3 ha farm because it actually sells its production through intermediaries; no simulation is therefore necessary.

Additionally, the scale inherent in sizable projects can minimize the fixed costs associated with bulldozers and the transportation of other machinery; there is also potential for bulk discounts. Watershed ponds are used for farms regardless of their dimension because they are cheap and speedily built. Therefore, despite the reduced construction costs of these larger ponds it did not compensate for their reduced yield; thus the pond cost per tonne of fish produced increased.

Other facilities include water pumping, pipework, storage building, electrical wiring, and, in large farms, wells, office and caretaker and night-guard houses. Facility-related costs per production unit decrease with farm size for small and medium farms because these fixed costs are similar. However, this factor increases in larger farms due to their expanded requirements. Larger farms also need wells, office, caretaker and night-guard houses, vehicles, and their costs increase with farm size. The need for efficient transport of fingerlings, feed and the workforce to and within the farms makes vehicles essential. Moreover, large ponds require boats for effective feed distribution and tractors for maintenance and harvest activities. Thus, they may induce a diseconomy of scale if they are not associated with technological improvements. Such infrastructure, while necessary, does not directly increase yield and leads to losses instead of profits.

Feed was the major portion of the operational costs, averaging 73% across the studied farms. This is within the values generally observed in pond-based freshwater aquaculture, which range from 50 to 80% (Boyd et al., 2020). Feed costs are defined by the feed's intrinsic value and its conversion efficiency (FCR). As farms expanded, their ability to negotiate feed prices improved due to the larger quantities purchased. However, several smaller farms managed to negotiate better prices through forming associations, a strategy also effective in places like Vietnam (Khiem et al., 2010). The choice of protein content in fish feed also affected costs. While several studies (Chagas et al., 2007; Melo et al., 2001; Izel and Melo, 2004) recommended a 28% protein content for tambaqui growth, many farms in our study opted for a 32% protein diet, which is about a third more costly. Thus, choosing the proper diet could substantially decrease production costs. Feed conversion ratios were variable, with the medium farms showing slightly lower values (close to 1.4). This value is similar to those obtained in farming various species in Brazil (Valenti et al., 2021) and other species worldwide, including tilapia (FAO, 2022). This FCR means that 1.4 kg of commercial diet containing about 90% of dry mass produces 1 kg of tambatinga, containing ~22% of dry mass. The efficiency is lower than 20%. This efficiency in assimilating commercial diets explains the high level of feed

Table 3
Values of each item of the total operating costs (TOC), in US$ per tonne of fish produced annually for each farm (shown in black). Costs of vertically integrated farms in the simulated scenario, in which these farms sell all production to intermediaries, are marked in red[1].

Farm (ha)	Feed (US$/t)	Labor (US$/t)	Energy (US$/t)	Fingerlings (US$/t)	Maintenance (US$/t)	Other (US$/t)	TOC (US$/t)
0.1	994	217	61	39	34	0.2	1,344
0.1	994	174	61	39	34	0.2	1,301
0.2	894	292	125	39	52	0.2	1,403
0.2	894	200	58	39	18	0.2	1,210
0.3	1,077	161	62	39	11	7.8	1,358
0.5	1,056	259	109	36	58	14	1,531
0.5	1,056	178	53	36	21	14	1,358
1.3	809	1,080	74	36	33	23	2,056
1.3	809	125	47	36	23	23	1,063
1.4	728	394	57	34	29	6.4	1,249
1.4	728	141	39	34	21	6.4	969
1.5	652	113	25	32	17	32	872
2.8	674	191	35	29	19	0.7	949
4.8	788	219	19	40	21	6.8	1,095
5.2	788	220	27	28	27	26	1,117
12	845	186	61	27	30	17	1,165
17	1,025	165	109	29	30	1.8	1,359
23	995	197	130	34	57	13	1,427
29	855	326	109	34	48	6.0	1,379
185	818	412	179	25	47	0.8	1,483
220	770	319	110	25	53	33	1,311

[1]This concerns the cost of labor, energy, and maintenance spent for commercializing the yield. The data shown under "other" consists of lime, telephone, taxes and the environmental license fee. Data is only shown in black for the 0.3 ha farm because it actually sells its production through intermediaries; no simulation is therefore necessary.

cost in fish monoculture. More than 80% of the commercial diet is lost to the environment. Integrating the culture of tambatinga with other species with complementary ecological functions may improve feed use (Thomas et al., 2021) and divide the feed cost among two or more crops. A strong improvement in FCR by integrating other species in freshwater pond fish farming has been demonstrated in cultures of tambaqui (Franchini et al., 2020) and lambari (*Astianax lacustris*) (Marques et al., 2021).

Labor costs, on average, accounted for 15% of the total operational expenses but could rise up to 25% in the largest farms. Lima et al. (2020) also estimated labor costs at 15% of the total operational cost for tambaqui culture in Amazonia. Smaller farms (up to 1.5 ha) demonstrated a decline in labor costs per unit of product as their size increased. At the 2.8 ha farm size threshold, labor costs began to rise. This shift aligned with the hiring of full-time workers, entailing added social contributions, which are 42% of wages. As farm size expanded beyond 4.8 ha there was a pronounced increase in labor demand per tonne of fish produced. This expansion involved varied job functions, including night guards to ensure security and supervisors to oversee operations. Larger farms also employed drivers, secretaries, housekeepers and accountants. Difficulties in managing large ponds necessitated personnel to drive tractors and boats, position nets and handle the crops. However, the 220 ha farm was an exception because it considerably reduced feeding labor by using feed spreading machines. The minimal mechanization observed in the studied farms potentially accounted for the elevated labor costs in larger farms. This contrasts with the findings of other studies that suggest that larger farms have lower labor costs (Filipski and Belton, 2018; Hossain et al., 2022).

The energy consumption is primarily driven by the fuel consumption of vehicles. To a lesser extent, electricity demands grew due to considerable water pumping from rivers or wells. Medium sized farms did not have vehicles, boats or electrical equipment, which kept their energy consumption low. Fingerlings are cheap because hatcheries are nearby; they contribute only about 4% to production costs. Maintenance of

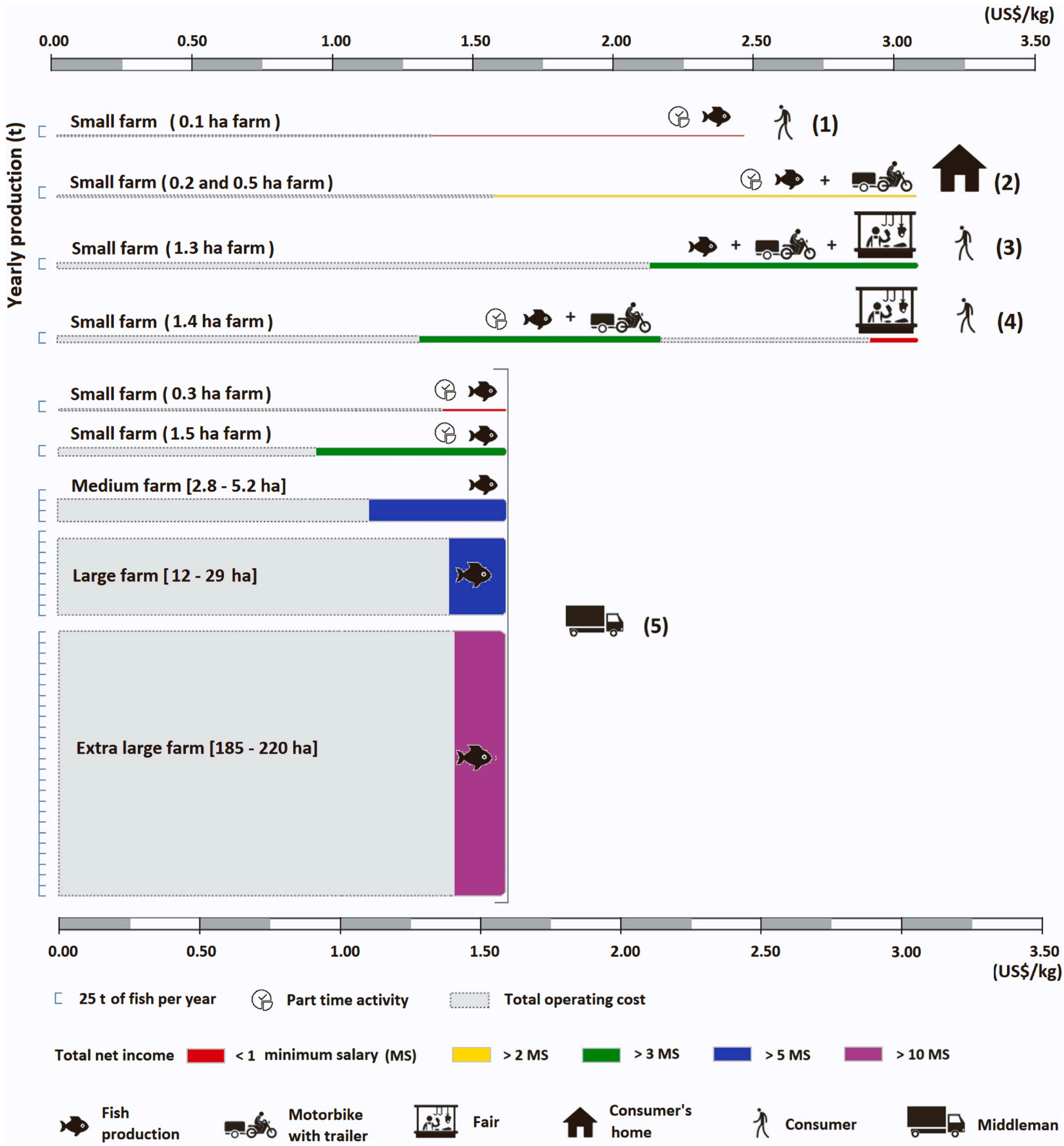

Fig. 6. Diagram of the fish marketing value chain of the various farms studied. Farms involved in the marketing value chain are in the following categories: farm-based sales (1); door-to-door sales (2); market sales (3); transporting to market traders (4); selling to middlemen (5). The horizontal axis shows the purchase and sale price of tambatinga (US$/kg), while the thickness of each row is proportional to the average yearly production or trade of tambatinga with a scale unit of 25 t. In each row, the light gray part represents the operating cost and the gray part represents the income of the different ventures. The farm of 0.5 ha used a car instead of a motorbike with trailer.
MS = minimum salary in the region (adapted from Gilson et al., 2023).

infrastructure and equipment is low because the facilities have minimal mechanization.

Tambatinga commercialization is based on farmer-controlled or intermediary-controlled supply/value chains (Gilson et al., 2023). Small farms generally operate in more than one level of the downstream supply chain, controlling the chain and obtaining higher prices. Medium and large farms rely on the intermediary-controlled chains; they are therefore forced to sell their fish at low prices determined by the intermediaries. All farms have positive net income (net revenues), but only small and medium farms (≤ 12 ha) have economic profit. An exception

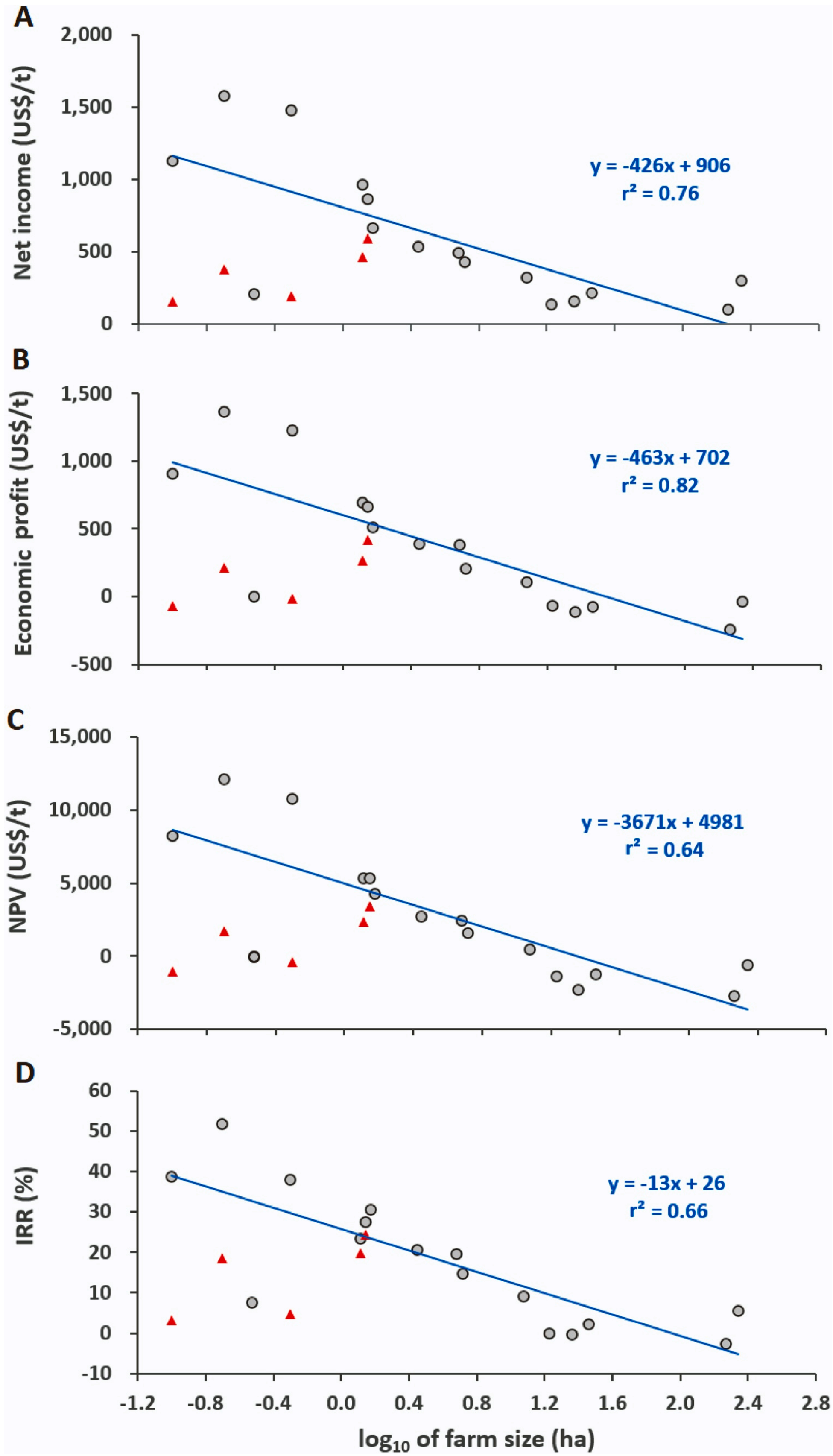

Fig. 7. Variation of Net Income (A), Economic Profit (B), Net Present Value (NPV, C) and Internal Rate of Return (IRR, D) in the various sized farms. Farm size is represented in the X-axis in log base10 of the farm size in hectares. The red dots represent the indicators obtained for simulating the trade to intermediaries of farms involved in a marketing value chain.

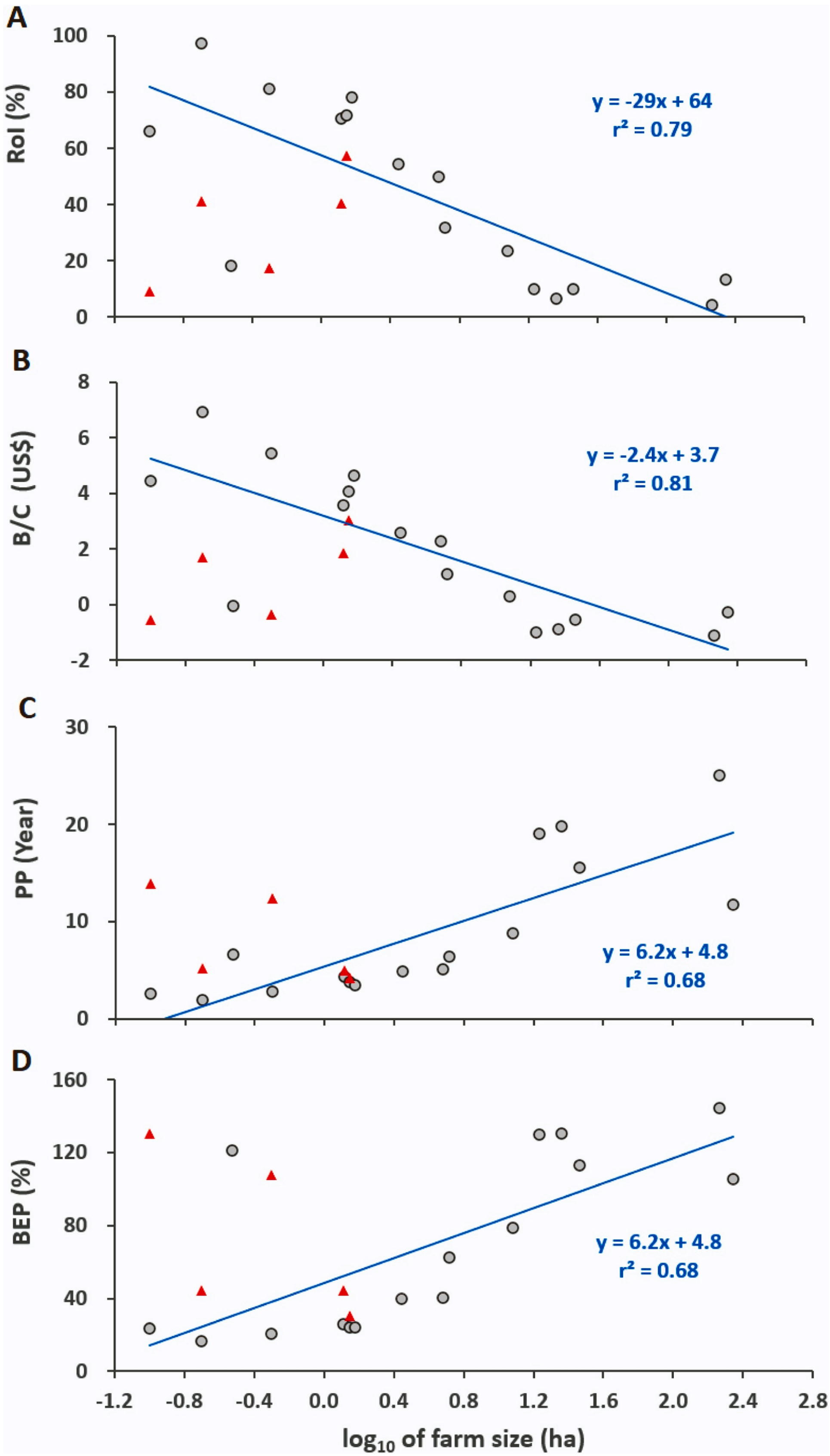

Fig. 8. Variation of Return on investment (RoI, A), Benefit-Cost Ratio (B/C, B) Payback Period (PP, C) and Break-Even point (BEP, D) in the different sized farms. Farm size is represented in the X-axis in log base10 of the farm size in hectares. The red dots represent the indicators obtained for simulating the trade to intermediaries of farms involved in a marketing value chain.

Table 4
Economic indicators obtained using the real values obtained by farmers. The Red values stands for the farms simulating the trade of all fish to middlemen. US$/t = US dollars per tonne of fish produced.

Farm size (ha)	Net Income (US$/year)	Net Income (US$/t)	Economic Profit (US$/t)	Net Present Value (US$/t)	Internal Rate of Return (%)	Benefit Cost Ratio (US$)	Return on Investment (%)	Payback Period (yr)	Break-Even Point (%)
0.1	1,805	1,128	909	8,230	39	4.5	66	2.6	24
0.1	250	156	-66	-1,012	3.2	-0.5	9.2	14	130
0.2	6,299	1,575	1,364	12,124	52	6.9	98	1.9	17
0.2	1,514	378	213	1,691	18.5	1.7	41	5.2	44
0.3	687	172	-36	-391	7.5	-0.3	16	6.6	121
0.5	8,872	1,473	1,229	10,744	38	5.5	81	2.8	20
0.5	1,135	189	-15	-421	4.8	-0.4	18	12	108
1.3	11,554	963	695	5,302	24	3.6	71	4.3	26
1.3	5,575	465	268	2,322	19.9	1.9	41	5.0	44
1.4	12,512	863	663	5,291	28	4.1	72	3.8	24
1.4	8,579	592	419	3,395	24.4	3.0	57	4.2	31
1.5	10,918	672	519	4,382	31.2	4.8	79	3.4	24
2.8	23,862	528	383	2,714	20.6	2.6	54	5.0	40
4.8	27,786	491	378	2,428	19.6	2.3	50	5.1	40
5.2	17,969	428	209	1,580	14.8	1.1	32	6.5	62
12	38,099	317	106	424	9.1	0.3	23	8.8	79
17	22,206	131	-72	-1,402	0.0	-1.0	10	19	130
23	23,439	156	-115	-2,280	-0.4	-0.9	6.5	20	130
29	41,871	211	-76	-1,260	2.3	-0.5	10	16	113
185	51,626	98	-247	-2,698	-2.8	-1.1	4.4	25	145
220	171,388	297	-36	-615	5.4	-0.3	13	12	105

was the 0.3 ha farm, which experienced losses because it was not involved in a value chain. In this farm, the net revenue may be considered a complementary family income to retain the owner in the activity. For larger farms, revenues covered operating costs but did not cover all land, capital and family/entrepreneurial labor costs. This scenario indicates that large farms may not survive in the long run because farmers can move to a more profitable activity in the future (Engle, 2019). Therefore, large tambatinga farms are not economically viable. Technological improvements and changes in management, especially in feeding practices, could be introduced to convert these farms into profitable businesses.

Net farm income represents the money received by the farm after paying all expenses (Engle, 2019). This value is significant for family farms because it means household earnings. Small farms significantly increased their net income by establishing a vertical integration and shortening the supply chain by eliminating intermediaries. Except for the 0.1 and 0.3 ha farms, small farms (≤ 1.5 ha) obtained a net income from US$ 6200 to 11,085, which is attractive for a family business in this region. The minimum legal salary and per capita income were US$ 3280 and US$ 2700 per year respectively, at the time of this study (IBGE, 2023b). Therefore the tambatinga small farm model that includes vertical integration allows small-land owners to maintain 2 to 5 people in a lifestyle compatible with their peers in the region. Medium farms (≥ 2.8 and ≤ 12 ha) did not use vertical integration, but are effective in obtaining net incomes from US $ 23.756 to US$ 38,099; these represent 7 to 9 times the minimum salary and 9 to 14 times the per capita income in the region. In addition, they have positive economic profit. These values are attractive for family businesses and are economically feasible. Only the farms ≥ 185 ha received a net income substantially higher than medium farms. The annual wage for a 4-person family sufficient to meet all living expenses was estimated to be about US$ 14,370 at the time of the present study (Dieese, 2016). Therefore the net income of medium farms considerably surpasses the requirements for a family to have food security, housing, health, education, clothing, sanitation, transportation, leisure and social security. On the other hand, small farms may provide an important complementary income.

Farm size significantly influenced financial feasibility indicators, which generally decreased as farm size increased. All indicators showed that small farms are more attractive as investments than the others, except the 0.3 ha farm because this one did not operate a vertical model. Therefore, the downstream value chain reduction is essential to increase economic gains. In farmer-controlled value chains, Benefit/Cost ratios hovered around US$ 4–5 for every invested US$ 1; return on investment was robust, ranging between 66% and 98%. The payback period spanned 2 to 4 years, and IRR fluctuated between 24% and 52%. In Brazil's aquaculture sector, a payback under 5 years and an IRR above 20% are considered attractive (personal observation). The breakeven points were close to 20%, which indicates high resilience to scenario shifts. However, medium-sized farms, particularly those of 5.8 and 12 ha, demonstrated reduced investment attractiveness. Increase in size may present management challenges, subsequently reducing productivity and undermining financial feasibility indicators. As the farm size increases, advancement in production technology should be made simultaneously to prevent declines in performance. Medium farms might consider vertical integration and participate in the downstream supply/value chain. If they did so they could trade fish for higher prices, increasing their economic performance. Indicators of financial feasibility confirmed that large farms are not attractive investments and are economically unfeasible. This is probably a result of their lower productivity compared to medium farms and both their lower productivity and selling prices compared to small farms because of the larger intermediary-controlled value chain.

Farm size efficiency is a much debated topic in both aquaculture and agriculture. However, less data is available about aquaculture and the results are controversial, depending on the area and the species studied (Guttormsen, 2002; Chand et al., 2011; Belton et al., 2012; Asche et al., 2013; Engle et al., 2017; Kumar et al., 2020; Khan et al., 2021; Hossain et al., 2022). Small-farm aquaculture (SFA) or small-scale aquaculture (SSA), which are characterized by limited assets, low operational costs and large family labor, are frequently considered suitable for combating poverty by enhancing food security and rural livelihood development (Bondad-Reantaso and Prein, 2009). However, this belief is controversial. Some scientists have advocated that commercial small and medium aquaculture enterprises (SMEs) are more efficient means to alleviate poverty (Brummett et al., 2008, 2011; Belton and Little, 2012; Little et al., 2012; Kassam and Dorward, 2017). SMEs would boost the economy more than SSAs, creating farm income and providing indirect benefits for those that are experiencing poverty by the creation of employment. The present study showed that the small tambatinga farms situated in a tropical region of South America (that match the concept of SSAs) are more efficient in generating wages than the SMEs (represented by the medium farms) when they control the value chain. The low production level allows the reduction of the value chain to one step, leading to a high selling price. Studies in the tropical regions of other countries should be performed to broaden this concept.

The enormous success of small tambatinga farms stems from their ability to implement vertical integration by incorporating downstream supply/value chains, shortening the steps between producers and consumers to one or no intermediaries. This ability doubled the fish selling price and boosted net income by 150 to 788%. In addition, small farms benefit from a stable local market, reducing transport costs, logistics, and cold chains. Vertical integration was also found to boost aquaculture success in Zambia (Kaminski et al., 2020). However, the understanding of vertical integration by low-income aquaculture owners needs further development (Gilson et al., 2023). Financial aid programs should be implemented to assist small farms in moving towards vertical integration. Another factor was that small farms formed associations; the collaboration with their peers allowed them to achieve collective benefits. This strategy is also effective in other countries, such as Vietnam (Khiem et al., 2010). These farm associations also fostered an enhancement in farmers` knowledge similar to that observed in other countries (Philip et al., 2016; Nguyen and Jolly, 2019). Thus, associations showcased proficient labor, assisted by technology transfer programs provided by government institutions such as the Brazilian Micro and Small Enterprises Support Service (Sebrae) and the Brazilian Agricultural Research Corporation (Embrapa). Small farms have similar benefits to those large farms by their associations with their peers.

Some studies have found that large-scale aquaculture farms (LSF) benefit from economies of scale by distributing fixed costs across increased production volumes (Engle, 2007; Engle et al., 2017; Duffy, 2009; Asche et al., 2013; Kumar et al., 2020). Notably, research on catfish farming in the United States has shown a continuous effect of economy of scale as farm size increases; this suggested that the ideal farm size may be upwards of 400 ha (Engle, 2007; Kumar et al., 2020). Generally, it is believed that LSF enhances benefits and uses high technology, equipment, a qualified workforce, and an organized administrative structure. However, the results of the present study showed that LSF in the midnorth (an important fish farming region in tropical South America) may fail to attain upscaling benefits because of deficiencies in facilities, management and marketing. Therefore, in the real world, aspects other than farm size may be more effective in driving the economic efficiency of an aquaculture system. Further studies should investigate if the length of the supply chain affects farm financial performance more than farm size.

A significant issue in analyzing the economic efficiency of aquaculture is to decide which production factors should be included. Many studies have neglected essential elements, such as the annualized costs of capital assets and family labor and management, particularly when viewed as noncash expenses (Engle, 2019). In addition, the heterogeneity of the analysed factors and methodological differences make comparisons among various studies difficult. In the present research, we have selected many variables that reflect economic efficiency and standardize the collection of data in farms of different sizes. Thus, our data allows robust comparisons among the farms studied.

In conclusion, our study of tambatinga aquaculture in a tropical region of South America has shown that the interactions between farm sizes and value chains were essential to explain economic performance. Small aquaculture farms could effectively boost rural economies and reduce poverty in developing countries when farmers control the value/supply chain. Low investment is enough to set up an infrastructure and allow a vertical business model. In addition, small farms may be attractive investments. Therefore, the implementation of small-scale aquaculture allows the achievement of the Sustainable Development Goals numbered 1 (no poverty), 2 (zero hunger), 8 (decent work and economic growth) and 16 (life below water) of Agenda 2030 (UN, 2015). Increasing farm size should only be done side by side with improvements in the technologies used, such as pond design, farm management, harvesting, storage and marketing; if not, larger enterprises may not be economically feasible.

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CRediT authorship contribution statement

F. Gilson: Conceptualization, Methodology, fieldwork and writing. **M. B. New**: Writing – reviewing and editing. **L. A. Rodrigues**: field work, reviewing. **G. W. Bueno**: reviewing. **W. C. Valenti**: conceptualization, methodology, writing, reviewing, and supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Wagner Cotroni Valenti reports financial support was provided by State of Sao Paulo Research Foundation. Wagner Cotroni Valenti reports financial support was provided by National Council for Scientific and Technological Development. Wagner Cotroni Valenti reports financial support was provided by Coordination of Higher Education Personnel Improvement. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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