

# Effects of distance and co-sale with pirarucu on the prices of alternative commercial fish species in community-based management systems in the Brazilian Amazon

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## ABSTRACT

Participatory co-management of pirarucu has been widely studied in the Amazon; however, there is little information on commercial species other than pirarucu itself. Economic theory and empirical evidence suggest that logistical constraints and commercialization strategies can significantly shape price formation in small-scale fisheries, influencing both fisher income and market efficiency. This study evaluates the effects of the joint sale of pirarucu with other species, the distance from the fishing grounds to the urban centers and type of fisher on the sale price of the alternative commercial species. We analyzed 71 records of commercial fish production, aggregated by species, year, and fishing agreement area, involving six economically important species in the Middle Solimões River (Amazonas, Brazil), using linear mixed models with species as a random effect. The distance from the communities to the urban centers varied from 19 to 120 km, while prices varied from US\$ 0.25 to 2.26/kg, being higher for *Colossoma macropomum* and lower for *Piaractus brachyomus* and *Cichla* sp. We found that distance tended to increase fish prices, although the effect was only marginally significant. This pattern may reflect an indirect effect, as more remote fishing areas are associated with larger individuals, which usually command higher prices. Type of fisher and joint sales with arapaima did not show robust effects on price. These findings suggest that distance plays a modest but relevant role in price formation, providing preliminary evidence that logistical factors, particularly distance to urban centers, influence multi-species value chains under participatory co-management in the Amazon.

**KEYWORDS:** *Arapaima gigas*; Alternative fisheries; sustainability; fishery management; fish price

## Efeitos da distância e da venda conjunta com pirarucu sobre os preços de espécies comerciais alternativas em sistemas de manejo comunitário na Amazônia Brasileira

### RESUMO

A co-gestão participativa do pirarucu tem sido amplamente estudada na Amazônia; entretanto, há pouca informação sobre espécies comerciais além do próprio pirarucu. A teoria econômica e as evidências empíricas indicam que restrições logísticas e estratégias de comercialização podem influenciar significativamente a formação de preços na pesca de pequena escala, afetando tanto a renda dos pescadores quanto a eficiência do mercado. Este estudo avaliou os efeitos da venda conjunta do pirarucu com outras espécies, da distância entre as áreas de pesca e os centros urbanos e do tipo de pescador sobre o preço de venda das espécies comerciais alternativas. Foram analisados 71 registros de produção pesqueira comercial, agregados por espécie, ano e área de acordo de pesca, envolvendo seis espécies de importância econômica no médio rio Solimões (Amazonas, Brasil), utilizando modelos lineares mistos com a espécie considerada como efeito aleatório. A distância entre as comunidades e os centros urbanos variou de 19 a 120 km, enquanto os preços oscilaram entre US\$ 0,25 e US\$ 2,26/kg, sendo mais elevados para *Colossoma macropomum* e mais baixos para *Piaractus brachyomus* e *Cichla* sp. Observou-se que a distância tende a aumentar os preços do pescado, embora o efeito tenha sido apenas marginalmente significativo. Esse padrão pode refletir um efeito indireto, uma vez que áreas de pesca mais remotas estão associadas à captura de indivíduos de maior porte, que geralmente alcançam preços mais altos. O tipo de pescador e as vendas conjuntas com o pirarucu não apresentaram efeitos consistentes sobre o preço. Esses resultados sugerem que a distância exerce um papel modesto, porém relevante, na formação de preços, fornecendo evidências preliminares de que fatores logísticos, especialmente a distância até os centros urbanos, influenciam as cadeias de valor multiespécies sob regimes de co-manejo participativo na Amazônia.

**PALAVRAS-CHAVE:** *Arapaima gigas*; pesca alternativa; sustentabilidade; manejo pesqueiro; preço do pescado

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## INTRODUCTION

Overfishing is recognized as being one of the main causes of declines in fish populations (Pauly *et al.* 2002; Hilborn *et al.* 2003; Allan *et al.* 2005). In the Amazon the overfishing of pirarucu (*Arapaima gigas* (Schinz, 1822)), which almost led to the extinction of the species, is an iconic case (Bayley and Petrere 1989; Queiroz and Sardinha 1999). The recognition of this serious threat has led to the implementation of natural resource management measures, such as conservation areas, to reduce the pressure on fish stocks (Queiroz 2005; Garcez and Sánchez-Botero, 2006). In addition to this measure, other strategies were adopted, the best-known being participatory co-management of pirarucu. In this model, local communities engage in fishing within protected areas for which they are also responsible for enforcement and protection, which results in sustainable exploitation of fish stocks, especially pirarucu, thereby contributing to its conservation (Viana *et al.* 2004; Campos-Silva and Peres 2016).

Participatory co-management of pirarucu is considered an efficient conservation tool (Carvalho *et al.*, 2025; Castello 2004; Gonçalves *et al.*, 2024; Viana *et al.* 2004; 2007), as it considers the participation of community members and results in a mutual benefit between the environment and its users (Campos-Silva and Peres 2016; Campos-Silva *et al.* 2019). Since its implementation in 1999, pirarucu stocks have recovered and, in return, provide a source of income for local populations that adhere to the participatory co-management of pirarucu (Viana *et al.* 2004). In addition, this system also benefits other fish species, given the protection status assigned to the lakes (preservation, maintenance, and commercialization) (Viana *et al.* 2004; Medeiros-Leal *et al.* 2021).

Several studies in the Amazon have demonstrated positive effects of the restricted access to potential fishing sites on the fish assemblages (Morales *et al.* 2019; Silvano *et al.* 2009; Medeiros-Leal *et al.* 2021; Nagl *et al.* 2021). In the lower Solimões/Amazon River, participatory co-management of pirarucu was associated with a significant increase in the abundance and richness of stocks, especially of mandubé (*Ageneiosus ucayalensis*), sardinha (*Triportheus albus*), piaba (*Tetragonopterus argenteus*), piracatinga (*Calophysus macropterus*) and curimata (*Curimata ocellata*) (Medeiros-Leal 2021). At the same time, no differences in the abundance of the 14 species of fish of interest to fishers were found between lakes with free or restricted access in the Mamirauá reserve, middle Solimões river (Silvano *et al.* 2009). However, these authors found a greater abundance of an important commercial fish, the tambaqui (*Colossoma macropomum* (Cuvier, 1816)), which was greater in lakes with restricted access. These results indicate that, when compared to areas with open access, the efficiency of the conservation of protected areas and the participatory co-management system benefit not only the management focal-species, pirarucu, but the entire assemblage of fish that use this environment to complete their life cycle.

Thus, the high abundance of species other than the pirarucu, a target species for participatory co-management, opens up the possibility of exploitation and commercialization, especially of species of commercial interest, a practice that is called “alternative commercial fishing” (IDSMS 2023). Alternative commercial fishing emerges as a source of extra income and ensures the maintenance of community management, since some of these species are among the most landed in the ports of the region, such as tambaqui and arowana (*Osteoglossum bicirrhosum*) (Cuvier, 1829) (Viana *et al.* 2004; Lopes and Freitas 2018).

Although there have been several studies regarding participatory community management focusing on pirarucu (Castello 2004; Viana *et al.* 2004; 2007; Campos-Silva and Peres 2016), little is reported about alternative commercial fishing and how much it contributes to these management systems. As such, studies on this theme are scarce, however essential, because their results can strengthen the success of participatory co-management, ensuring both the generation of income for the communities and the conservation of fish stocks in the region. Therefore, the present study aimed to evaluate the alternative fishing of commercial species in the Mamirauá and Amaná sustainable development reserves, in the Central Brazilian Amazon, and test the hypothesis that the sale price of commercial alternative species is not influenced by the distance from the community to the nearest urban center, type of fisher, fishery production and their joint sale with the pirarucu. The explanatory variables were selected based on ecological, economic, and logistical considerations documented in the literature on Amazonian fisheries.

We expected a positive effect of the distance to urban center on the sales price, based on the assumption that more remote fishing areas are less exploited, more preserved, and tend to yield larger individuals, which are more valuable (Castello *et al.* 2015; Keppeler *et al.* 2018). We expected urban fishers to achieve higher prices, due to better access to markets, improved infrastructure, and stronger negotiation capacity (Jimenez *et al.*, 2020). We anticipated a negative relationship between the fishery production and the sales prices, under the assumption that higher volumes of fish landed may lead to oversupply and a decrease in unit prices. A negative effect of the joint sales with pirarucu on the alternative species sale prices was expected, as bundling alternative species with pirarucu could reduce their individual market value, especially when high- and low-value species are sold together as a lot (Fernandes *et al.* 2007; Amaral 2007).

## MATERIALS AND METHODS

### Study area

The study was conducted in the Amaná and Mamirauá sustainable development reserves (SDRs), which are located in the municipality of Maraá, Amazonas. The Amaná SDR

comprises an area of approximately 23,489.62 km<sup>2</sup>, and has 4,503 residents, distributed in 133 communities and approximately 182 users of the reserve who do not reside within the reserve (Sociedade Civil Mimirauá 2020). The Mimirauá SDR comprises an area of approximately 11,240 km<sup>2</sup> with 1,668 residents and about 3,600 external users of the reserve (Sociedade Civil Mimirauá 2014). In these two protected areas, fishing agreements are established for the management of fishery resources.

### Commercial Arrangements in the Study Areas

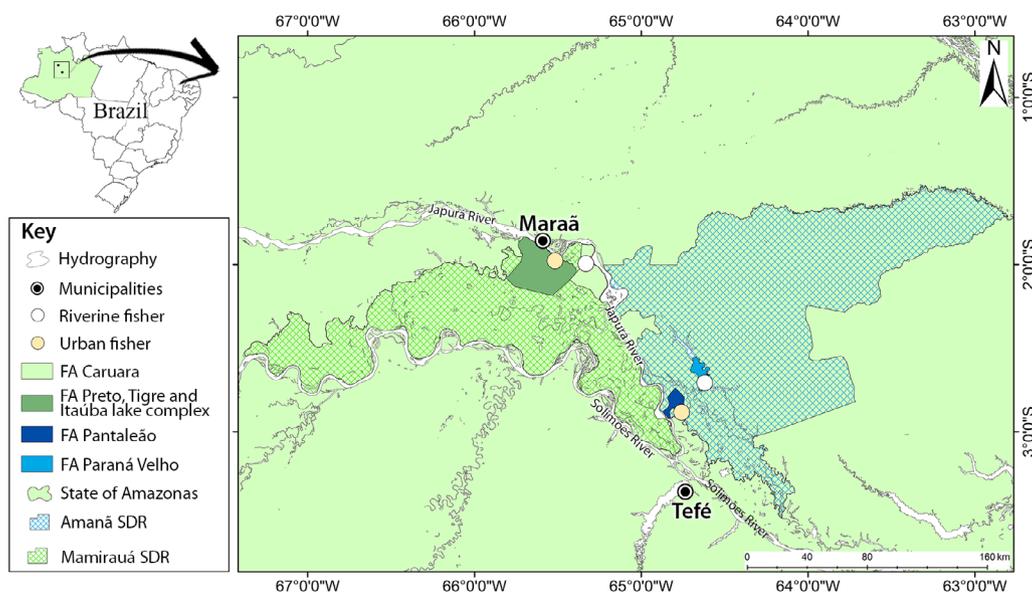
Fish commercialization in the Mimirauá and Amaná Sustainable Development Reserves takes place through different strategies, which vary depending on the type of fisher and the available infrastructure. In general, three main commercialization modalities are observed. *Direct sales to local markets and consumers:* Riverine fishers often sell their catch directly at community fairs or to small local vendors. These transactions are mostly informal and involve low logistical costs. Prices obtained in these sales are often higher than those offered by intermediaries; however, the volumes traded are usually very small, limiting the overall income generated. *Sales to middlemen and intermediaries:* Both riverine and urban fishers may sell their fish to middlemen, who collect the product directly in the communities or at designated delivery points. This practice is common in more remote areas, as it reduces transaction costs and risks for the fishers. However, dependency on a single buyer and low transparency in price formation usually lead to reduced compensation. *Structured commercialization initiatives:* Riverine and urban fishers involved in participatory co-management programs take part in more structured commercial arrangements. In these models, fishers and buyers

meet in advance to negotiate the terms of the transaction, such as volumes, logistics schedules, and prices, often through pre-established contracts. This process increases transparency, improves predictability, and enables fishers to select the most economically advantageous arrangements. As a result, it strengthens their decision-making capacity. A notable example is the role of Associação dos Produtores Rurais de Carauari (ASPROC, Association of Rural Producers of Carauari), which currently leads the commercial arrangements of the Gosto da Amazônia ([www.gostodaamazonia.com.br](http://www.gostodaamazonia.com.br)) initiative in the region. Through ASPROC, Gosto da Amazônia promotes the sustainable commercialization of fish with traceability, especially pirarucu, by establishing certified value chains, partnering with multiple community management groups, and expanding market reach to both national and international buyers.

Although not all transactions in the study areas occur through these structured circuits, such initiatives contribute to greater price stability, promote proper species separation, and encourage improved quality control practices, directly benefiting the participating fishers. The diversity of commercialization arrangements reflects the challenges faced by small-scale fishery value chains in the Amazon, particularly in terms of market access, logistical infrastructure, and institutional support. These aspects are relevant for interpreting price variability, although they were not directly included in the statistical models of this study.

### Data collection

For this study, four areas with fishing agreements were selected, two in the Amaná SDR and two in the Mimirauá SDR (Figure 1). Fishers were categorized as riverine or urban. Riverine fishers are traditional residents of communities located inside



**Figure 1.** Location of the four areas with fishing agreements (FA) within the territorial limits of the Amaná and Mimirauá sustainable development reserves, on the middle Solimões River, Central Amazon. This figure is in color in the electronic version.

or near the Mamirauá and Amaná Sustainable Development Reserves and participate in regulated commercial fishing under community-based management agreements. Urban fishers, in contrast, are residents of municipal centers such as Tefé and Maraá and are also involved in commercial fishing, through formal agreements. Both groups engage in commercial fisheries but differ in terms of market access, logistics, and infrastructure.

In the Amaná SDR, two fishing agreement (FA) areas were selected: Paraná Velho, which is composed of riverine fishers, and Pantaleão, composed of urban fishers. In the Mamirauá SDR, the selected areas were Caruara, composed of riverine fishers, and the Lago Preto–Itaúba–Tigre complex, composed of urban fishers (Figure 1). These distinctions reflect the fisher's residence and logistical profile, not their legal status or fishing rights, as both groups are part of regulated management agreements.

The data used came from the database of the Fisheries Management Program of the Institute for Sustainable Development Mamirauá (IDSM). Information available in the annual technical reports for these four areas of fisheries agreements was used, which contained information on the capture and marketing of fish over seven years (2016–2022). Fish selling prices were converted from Brazilian reais (R\$) to US dollars (US\$), using the annual average exchange rate in the reference years of the data from 2016 to 2022, ranging from US \$ 3.1920 to US \$ 5.3950 (Ipeadata 2024).

For each FA and year, we compiled records of six commercially important species (Supplementary Material, Table S1). Alternative fishing occurs depending on the fish assemblage. Thus, for the study, we selected species of commercial interest in the region and representatives of the main taxonomic orders of fish: Osteoglossiformes (arowana, *Osteoglossum* sp.), Characiformes (pirapitinga, *Piaractus brachypomus* (Cuvier, 1818) and tambaqui, *Colossoma macropomum* (Cuvier, 1816), Siluriformes (Surubim, *Pseudoplatystoma* sp.), Cichliformes (peacock bass *Cichla* sp.) and Acanthuriformes (pescada, *Plagioscion* sp.).

### Data analysis

The unit of analysis was a species–area–year commercialization record. Each record included: (i) mean sale price (US\$/kg), (ii) annual production of that species in the FA (kg), (iii) distance (km) from the community to the nearest urban center (Tefé or Maraá), and (iv) whether the sale occurred jointly with pirarucu (0 = no; 1 = yes). In total, we analyzed 71 records: arowana (n = 18), pirapitinga (n = 9), tambaqui (n = 15), surubim (n = 11), peacock bass (n = 11) and pescada (n = 7) (Supplementary Material, Table S1). Records are considered independent because they represent distinct species–area–year combinations, not repeated measures of individual transactions. Descriptive analysis was performed to estimate the range, mean and standard deviation of the variables (Zar 2010).

For inference, we fitted linear mixed-effects models (LMMs) with Gaussian error distribution (lme4 package; Bates *et al.* 2015), including species as a random intercept. The full model included four predictors defined a priori: the distance from the community to the nearest urban center (the municipalities of Tefé and Maraá, Amazonas); the type of fisher (0 = riverine, 1 = urban); total fishing production (in kg); whether the sale was conducted jointly with pirarucu (0 = no, 1 = yes). It is important to note that distance and type of fisher varied only at the level of fishing agreement (four areas), limiting the effective replication of these predictors.

Given the limited sample size (n = 71) relative to the number of predictors, we tested two models: one including production (AIC = 98.74) (Supplementary Material, Table S3) and one excluding production (AIC = 72.99). Since the model without production had the lower AIC, it was retained for inference (AIC; Burnham and Anderson, 2002). Results are reported as coefficients  $\pm$  standard errors, with confidence intervals and p-values based on Satterthwaite's approximation (*lmerTest*; Kuznetsova *et al.*, 2017). Given the limited replication within species, we did not conduct species-level analyses and instead focused on identifying general patterns across the dataset.

Homoscedasticity and normality of residuals were checked by residual and Q-Q plots (Supplementary Material, Figure S1A and Figure S1B) (Zuur *et al.* 2009). Collinearity was assessed using the variance inflation factor (VIF < 5; Dormann *et al.*, 2013) from the car package (Fox and Weisberg 2019) (Supplementary Material, Table S2). Model fit was evaluated using marginal and conditional R<sup>2</sup> (Nakagawa and Schielzeth, 2013), calculated with the MuMIn package (Bartoń, 2025). All analyses were carried out using R software, version 4.3.1 (R Core Team 2023).

## RESULTS

The distances from the communities to the nearest urban center (municipalities of Tefé and Maraá, Amazonas) ranged from 19 to 120 km (Table 2). The fishery production of the species ranged from 3.60 to 71,009.00 kg, with the lowest being obtained for *Plagioscion* sp. and the greatest for *Osteoglossum* sp. (Table 2). The selling price of fish per kilogram (US\$) ranged from 0.25 to 2.26, with the lowest value being paid per kg of *Piaractus brachypomus* and *Cichla* sp., and the highest value being paid per kg of *Colossoma macropomum* (Table 2).

In the linear mixed-effects models (n = 71), distance to the nearest urban center had a marginally positive effect on sale price (estimate = 0.0030  $\pm$  0.0016, p = 0.058; Figure 2). Type of fisher (riverine vs. urban) and joint sales with pirarucu were not significant predictors (p > 0.05, Table 3, Figure 2a). The marginal R<sup>2</sup> (R<sup>2</sup><sub>m</sub> = 0.061) indicated that fixed effects explained about 6% of the variance in prices, while the conditional R<sup>2</sup> (R<sup>2</sup><sub>c</sub> = 0.587) showed that species (the random effect) accounted for approximately 58% of the variance. Thus, most of the variation in prices is attributable to differences among species.

**Table 1.** Variables used in the study to evaluate alternative fisheries in the Amanã and Mamirauá sustainable development reserves, on the middle Solimões River, Central Amazon.

Variables		Description
Variable response	Selling price of fish kg <sup>-1</sup> (US\$) – FSP	Continuous variable: selling price of fish kg <sup>-1</sup> (US\$)
Explanatory variables	Distance (km)	Continuous variable: distance (km) from the community where the fishing was carried out to the nearest urban center (municipalities of Tefé and Maraã, Amazonas)
	Type of fisher	Categorical variable: 0 = riverine and 1 = urban. A riverine fisher resides in communities where there is community management of the pirarucu. Typically, these communities are far from urban centers. An urban fisher resides in urban centers, such as the municipalities of Tefé and Maraã, in the Amazonas state.
	Fishery production (kg)	Continuous variable: total catch of fish (kg)
	Joint sale	Categorical variable: joint sale of the species with pirarucu? 0 = no and 1 = yes

**Table 2.** Summary of the descriptive statistics for the variables used to evaluate drivers of sale prices of alternative fish specie in the Amanã and Mamirauá sustainable development reserves, in the region of the middle Solimões River, Central Amazon. N = number of records, corresponding to species–area–year commercialization units.

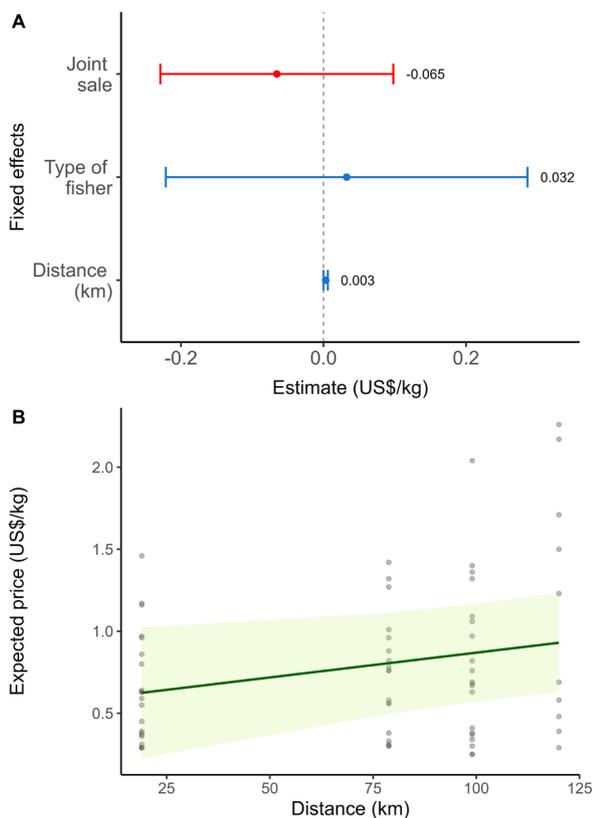
Species	N	Distance (km)	Fishery production (kg)	Selling price of fish kg <sup>-1</sup> (R\$)	Selling price of fish kg <sup>-1</sup> (US\$)
All	71	19.00 - 120.00 (70.92 ± 38.08)	3.60 – 71,009.00 (10,262.29 ± 16,873.85)	1.00 - 10.54 (3.16 ± 2.00)	0.25 - 2.26 (0.77 ± 0.47)
<i>Osteoglossum</i> sp. (arowana)	18	19.00 - 120.00 (63.44 ± 36.91)	10.00 – 71,009.00 (25,488.91 ± 23,608.37)	1.00 - 3.00 (1.55 ± 0.49)	0.29 - 0.56 (0.36 ± 0.07)
<i>Piaractus brachipomus</i> (pirapitinga)	9	19.00 - 120.00 (72.42 ± 39.00)	86.00 – 10,923.00 (2,341.08 ± 3,356.04)	1.00 - 7.00 (2.67 ± 1.96)	0.25 - 1.36 (0.60 ± 0.35)
<i>Colossoma macropomum</i> (tambaqui)	15	19.00 - 120.00 (73.89 ± 41.26)	377.00 – 42,671.00 (12,773.71 ± 13,722.18)	2.92 - 7.76 (5.21 ± 1.15)	0.80 - 2.26 (1.38 ± 0.40)
<i>Pseudoplatystoma</i> sp. (surubim)	11	19.00 - 120.00 (70.05 ± 40.54)	6.00 – 1,090.80 (538.66 ± 430.45)	1.50 - 10.54 (3.87 ± 2.30)	0.29 - 2.04 (0.96 ± 0.44)
<i>Cichla</i> sp. (peacock bass)	11	19.00 - 120.00 (79.02 ± 30.87)	5.00 – 3,502.00 (1,098.81 ± 966.80)	1.00 - 3.45 (2.50 ± 0.66)	0.25 - 0.82 (0.64 ± 0.16)
<i>Plagioscion</i> sp. (pescada)	7	19.00 - 120.00 (70.49 ± 35.40)	3.60 – 14,352.00 (5,590.66 ± 6,502.29)	2.00 - 5.00 (2.84 ± 0.98)	0.39 - 0.97 (0.68 ± 0.18)

**Table 3.** Values obtained in the linear mixed model (LMM) for the value per kg (US\$) of alternative fish species, evaluating the effects of distance, type of fisher (0 = riverine; 1 = urban) and joint sale (0 = no; 1 = yes). The marginal R<sup>2</sup> (R<sup>2</sup><sub>m</sub> = 0.061) indicated that fixed effects explained little variation in fish prices, while the conditional R<sup>2</sup> (R<sup>2</sup><sub>c</sub> = 0.587) highlighted that most variation was attributable to differences among species. Model AIC = 72.99836.

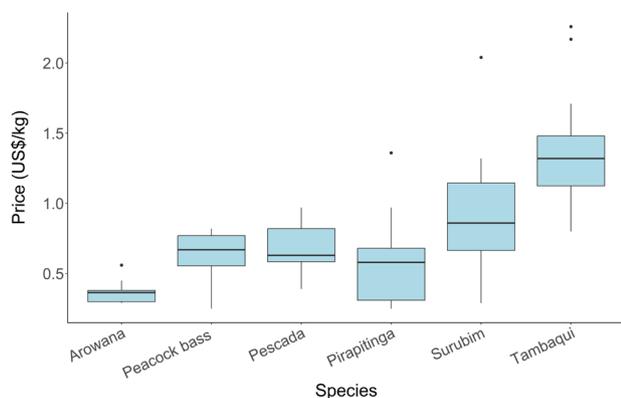
Fixed effects	Estimate	Standard error	df	t-value	p-value
(Intercept)	0.567	0.220	25.38	2.577	0.0162 *
Distance (km)	0.003	0.002	62.59	1.931	0.0580 .
Type of fisher	0.032	0.129	62.79	0.251	0.8027
Joint sale	-0.065	0.083	63.14	-0.785	0.4353

Number of observations = 71, groups: species = 6. Significance level: \* p<0.05; . p<0.01.

There was strong price variation across species (Figure 3), with higher values for *Colossoma macropomum* and lower values for *Piaractus brachypomus* and *Cichla* sp.



**Figure 2.** Fixed effects on fish price (US\$ per kg) estimated by a linear mixed model (LMM), with 95% confidence intervals, in the Mamirauá and Amaná Sustainable Development Reserves (Central Amazon, Brazil). (A) Model predictors included distance (km) to the nearest urban center, type of fisher (urban vs. riverine), and whether the sale was conducted jointly with pirarucu. (B) Effect of distance (km) to the urban centers (Tefé and Maraã, Amazonas, Brazil) on the expected fish price (US\$ per kg). Dots represent observed values, the green line indicates the model prediction, and the shaded area shows the 95% confidence interval.



**Figure 3.** Variation in fish sale prices (US\$ per kg) among the species analyzed in the Mamirauá and Amaná Sustainable Development Reserves (Central Amazon, Brazil). The boxplot shows that species is the main factor associated with price formation.

## DISCUSSION

Price formation in small-scale fisheries is a multidimensional process shaped by ecological, logistical, and institutional factors. In our study, species were the main factor explaining price variation, in line with previous research that emphasizes the role of biological traits and consumer demand in determining fish value (Batista *et al.*, 2012; Begossi *et al.*, 2011). This strong species effect may have reduced the relative influence of other predictors, especially in multispecies records.

Distance (km) showed a marginally positive effect on fish price. Although not statistically robust, this tendency is consistent with studies conducted in the Amazon, which suggest that fishing areas located farther from urban centers tend to experience lower fishing pressure and more favorable environmental conditions, resulting in larger individuals (Petrere 1986; Castello *et al.* 2015; Tregidgo *et al.* 2017; Keppeler *et al.* 2018; Lubich *et al.* 2021). In this region, where fish are commonly sold by weight (Honda 1972; Gandra 2010; Silva *et al.* 2020), larger individuals typically receive higher prices. Although our results suggest that distance may act as a proxy for this effect, we were unable to test the direct role of fish size because such data were not available in the records analyzed. Future studies should incorporate size measurements to disentangle the relative effects of distance and body size on price formation. In addition, greater distances may also signal relative geographic isolation, potentially reducing buyer competition and contributing to higher prices. However, it is important to note that distance and type of fisher varied only across four fishing agreement areas. This low effective replication limits statistical power and means that inference for these predictors should be interpreted with caution.

Contrary to expectations from the literature, we did not identify statistically robust differences in prices between urban and riverine fishers ( $p > 0.05$ ). The direction of the coefficient was consistent with the hypothesis of higher prices for urban fishers, which is often attributed to greater proximity to markets, better transportation, improved access to price information, and stronger bargaining power (Jimenez *et al.* 2020; Amaral 2007). However, the estimate was imprecise in the multispecies arrangement. Several mechanisms may explain this result. First, price formation in the study area appears to be strongly influenced by species (included as a random effect), which may attenuate group-level differences when records pool multiple species. Second, unobserved factors such as market saturation, availability of cold-chain infrastructure, and local competition among buyers, documented in previous studies (Amaral 2007; Jimenez *et al.* 2019), were not directly measured and may have masked contrasts between groups. Third, statistical power is limited by the total number of records and the low replication within species, restricting species-specific inference. Future research should (i) increase replication within species, (ii) collect direct measures of access to information, refrigeration infrastructure, and buyer competition along the value chain (Jimenez *et al.*

2020), and (iii) apply hierarchical models at the species level to disentangle group effects from interspecific heterogeneity.

Joint sales with *Arapaima gigas* did not show a significant association with prices in the general model ( $p > 0.50$ ). This result adds to the mixed evidence reported in the literature: in southern Brazil, multispecies lots were associated with lower fisher income and greater buyer control (Fernandes *et al.*, 2004), whereas in Moorea, French Polynesia, multispecies sales increased aggregate prices (Nassiri *et al.*, 2021). In our case, several factors may have attenuated the expected effect. First, the binary indicator of co-sale likely obscures variation in lot composition, as it does not capture the relative contribution of each species. Second, even within co-sale transactions, substantial heterogeneity in the proportion of pirarucu and alternative species can lead to divergent pricing outcomes. These two layers of variability reduce the ability to detect a consistent effect of bundling. Third, the high perishability of fresh fish and the lack of adequate cold-storage infrastructure in remote communities (Amaral 2007; Jimenez *et al.*, 2019) may reduce price differentials between joint and separate sales. To strengthen inference, future studies should (i) quantify the relative contribution of each species within mixed lots, (ii) distinguish prices negotiated at the point of acquisition from those at final resale (Reid 2004; Santos and Santos, 2005), and (iii) exploit exogenous variation in commercialization structures, such as the introduction of cold-storage facilities or logistical bases, to identify causal effects.

The study has broader implications for understanding how equity and sustainability are shaped in participatory co-management systems. As emphasized by Campos-Silva *et al.* (2018), pricing mechanisms directly influence income distribution in Amazonian fisheries. Although distance was positively associated with prices, this effect may operate indirectly, with remoteness serving as a proxy for larger fish sizes, a variable not directly available in our dataset. Thus, our policy considerations should be interpreted as exploratory, highlighting the need for future studies that explicitly test body size effects before deriving firm market recommendations. In this context, market differentiation instruments such as certification, traceability schemes, or geographical indications may reinforce these pricing mechanisms by enabling products from remote areas to achieve greater recognition and value (Gonçalves *et al.* 2025; Farias 2025; Souza *et al.* 2024). Future research should examine how these initiatives interact with the drivers identified here to promote both economic resilience and sustainable fisheries management.

Finally, these findings can inform the development of public policies that integrate commercialization strategies, equitable value distribution, and improved market access for fishers. Promoting sustainable fisheries in the Amazon demands more than ecological management; it requires inclusive governance, transparency in the value chain, and alignment with global frameworks such as the FAO

Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries (FAO, 2015, 2017) and the United Nations Sustainable Development Goals (United Nations, 2024). The results should be interpreted with caution, but they offer practical insights for policies and initiatives that aim to align community-based management with the strengthening of fair and resilient fishery value chains in the Amazon.

## CONCLUSIONS

Our findings provide preliminary evidence that logistical factors, particularly distance to urban centers, shape price formation in multi-species value chains under participatory co-management. Despite residual uncertainty and low within-species replication, these results offer a practical basis for aligning community-based management with strategies for value addition and market differentiation of Amazonian fish products.

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