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ABSTRACT

The study is an analysis of fish farming poles in the Brazilian Amazon, since they work as both income source and food security solution, besides being essential to achieve sustainable economic development. Local Moran's I (LISA), in combination to growth rate estimated by linear regression, was applied to detect municipalities with the potential to become "agropoles". According to the results, there are "fields of force" settled along the Amazonian borders, mainly in Rondônia and Roraima states. Native species "tambaqui" (*Colossoma macropomum*) production prevails in both states, while some clusters have incorporated multiple native species. This approach reduces financial loss risks and enhances regional production potential. Study findings point towards significant opportunities to create new sustainable aquaculture poles across the Brazilian Amazon. This process depends on sector-specific challenges to be overcome through coordinated efforts by producers and policymakers.

Keywords: Growth poles; Amazon fish farming; Sustainable economic development.

RESUMO

A pesquisa é uma análise dos polos de piscicultura na Amazônia brasileira, onde a atividade surge como alternativa para geração de renda e solução à segurança alimentar, além de promover o desenvolvimento econômico sustentável. O Índice Local de Moran (LISA), em combinação com a taxa de crescimento estimada por regressão linear, foi aplicado para detectar os municípios com potencial para se tornarem "agropolos". De acordo com os resultados, os "campos de forças" concentram-se nas bordas da Amazônia Legal, com destaque para Rondônia e Roraima. O tambaqui (*Colossoma macropomum*) prevalece nesses estados, porém há *clusters* que incorporaram múltiplas espécies nativas. Essa abordagem reduz riscos de perdas financeiras e amplia o potencial produtivo regional. As conclusões do estudo sugerem que a região amazônica possui excelentes condições para o surgimento de novos polos aquícolas sustentáveis. A concretização desse processo dependerá da capacidade de coordenação entre produtores e formuladores de políticas públicas para superar os desafios setoriais inerentes.

Palavras-chave: Polos de crescimento; piscicultura amazônica; Desenvolvimento econômico sustentável.

INTRODUCTION

The Amazonian aquaculture sector presents increasingly economic (Pedroza Filho; Rocha, 2024) and sustainable potential (Pincinato; Asche, 2016) to mitigate social and environmental issues (Froehlich *et al.*, 2018). Unlike cattle ranching, which is a traditional livestock activity that was promoted by policymakers in the 1960s and 70s to cover vast wildlife areas in the rainforest (Mello, 2006), fish farming can reduce the need for deforestation, land expropriation and biodiversity loss (McGrath *et al.*, 2020). These environmental issues lead to soil degradation and, consequently, to high greenhouse gas emissions into the atmosphere, besides intensifying climate changes (Assad; Martins, 2022).

Although fish farming has been currently used as sustainable alternative in the Brazilian Amazon, it still lacks proper organization (Oliveira *et al.*, 2024). It is so, because this activity faces insufficient technical and financial support, low human capital and high costs with inputs, as similarly observed in other Brazilian regions (Melo *et al.*, 2010). Public institutions, such as the Fishery and Aquaculture Unit of the Brazilian Agricultural Research Corporation, also known as Embrapa, in Palmas City, capital of Tocantins State (TO), Legal Amazon (Brasil, 1953), are working through project "BRS Aqua" to develop new technologies and institutional arrangements aimed at improving fish producers' competitiveness. Among many goals, this endeavor focuses on organizing data and information to better understand this sector's spatial distribution based on images in a geographic interface called "SITE Aquicultura" (Ummus *et al*., 2020).

Fish farming chain mapping in Brazil aims at making knowledge sharing with other institutions, such as authorities involved in regional development, easier. These policymakers are deeply influenced by space and territory concepts at the time to formulate economic growth, interregional equilibrium and hinterland's integration strategies (Serra, 2003; Alves *et al.*, 2024). The "theory of growth poles" was one of the theoretical frameworks guiding the occupation process in the Brazilian Amazon back in the 1970s (Perroux, 1950). This approach led to Manaus Free Trade Zone (ZFM), which was launched in Amazonas State capital (Silva *et al.,* 2021), as well as to regional poles settled for agriculture projects in Pará (Borges, 2014) and Tocantins (Arruda; Valdevino, 2014) states.

The concept of growth poles by François Perroux remains as valuable framework for the elaboration of regional development programs aimed at mitigating social inequalities (Oliveira; Oliveira, 2015; Lima, 2018). However, this model must adopt practices focused on ecosystem preservation and on the stable creation of new job positions (Lima, 2021). According to this understanding, regions holding such poles, like fish farming, have the necessary conditions to ground sustainable economic development principles. The aim of the present study was to identify fish farming poles in the Brazilian Amazon by addressing this issue as key factor for policymakers. Recognizing these centers can be the way to help exploring alternatives to reduce aiquiculture sector vulnerabilities and to provide the necessary conditions to implement sustainable projects aimed at mitigating deforestation and climate change in the regions they are located in, as well as at subsidizing public policymakers' accurate decision-making.

Accordingly, the following section discusses the concept of growth poles to guide fish farming sector sustainability in the Brazilian Amazon. The methodological approach and result discussion sectors are also presented. The final section provides conclusive insights based on the conducted investigation. The present research was entirely conducted at Embrapa Geoprocessing Laboratory, at the Fishery and Aquaculture Unit (Palmas-TO). It was funded by two key projects: "Carbon Footprint and Impacts of Aquaculture Expansion in the Amazon" (Calling Amazônia+10/CONFAP) and "Aquaculture as Sustainable Alternative in Cattle-Ranching Areas in Legal Amazon" (Calling Profix – FAPT/CNPq), which are coordinated by PhD Balbino Antônio Evangelista, from Embrapa Fishery and Aquaculture Unit.

THEORICAL FRAMEWORK

“Field of forces” are one of the three economic space components, and they are formed by poles or centers (Perroux, 1950). Furthermore, they attract and repel companies’ supplies and demands within their space, which results in networks arising from monetary flow. The analysis focuses certain industries highly capable of holding capital, the so-called propulsive industries, which are seen as potential pathways to reach economic growth (Perroux, 1955). These “growth poles” tend to spread effects on their environments and, consequently, to dominate other associated industries, either through inputs (backward linkages), new outputs (forward linkages) or through both (Hirschman, 1958).

Turning an abstract theory into a more operational framework was a way to enhance the theory of poles and to include homogenous (uniformity), polarized (hierarchy) and planning (government) space definitions in it (Boudeville, 1968). These concepts originality allowed setting boundaries around regions holding propulsive industries, besides opening a window of opportunities to expand this approach by including variables other than economic factors, such as social, political, cultural and psychological aspects, to it (Darwent, 1969). This framework is easy to understand; therefore, it leads to the application of this terminology in different contexts by different professionals who sought tools to solve regional issues (Serra, 2003).

Developing rural economies where agriculture could be a key sector to induce backward (e.g., seed, chemicals, equipment) and forward effects (e.g., food and cooking oil industry) is a recurring issue for regional studies. Infrastructure should be up-to-date in order to make products’ efficient trading easier in international markets (North, 1961). Simultaneously, the government should implement long-term exports-revenue investments in education and culture. This policy would ensure the establishment of local consumption markets and workforce conducive to economic diversification. It would avoid the formation of polarized spaces featured by remarkable social inequalities (Lima, 2003).

Rural economies tend to only focus one activity in case of lack of endogenous improvements, and it often leads to cash crops. Regional economic specialization can be mitigated by “agricultural growth poles” or “agropoles” implementation, since they work as starting point for scholars and governments to identify the proper sector types and companies to be attracted to a planning space (Picard *et al.*, 2017). These areas head toward optimizing agricultural sector management in order to support increased yield and domestic income through linkage effects (Surya *et al.*, 2021). Agro-spaces boundaries are defined by crops' dispersion level, by agroindustry extension and by the association between urban centers and rural properties (Oliveira; Rodrigues, 2019).

An agro-pole, such as the soybean complex, requires substantial investments in infrastructure and technology, and it demands regions to focus on profitable chains (Castro *et al*.; 2015; Doerner *et al*., 2019; Oliveira *et al.*, 2020). This preference is inevitable in a competitive system whose consumers and producers strive to boost their economic interests. A similar scenario is observed in the freshwater fish sector, whose well-known trading species, such as common carp (*Cyprinus carp*), Nile tilapia (*Oreochromis niloticus*) and pangas catfish (*Pangasius hypophtalmus*), are highly preferred by producers due to their advanced technological development and low cost (Moro *et al.*, 2013). These non-native varieties could widely spread in Brazilian ecosystems, and it would threaten local biodiversity. Consequently, authorities in Brazil and abroad, have enacted laws and regulations to mitigate the ecological and social impacts of biological invasions (Wang *et al.*, 2023).

Evidence supports the adoption of native species as key strategy to value local wealth (Pincinato; Asche, 2016), given the urgent need for balancing the conservation of natural resources and for achieving economic development in Brazilian agriculture (Pacheco *et al.*, 2025. Brazil is fortunate to have large hydrological basins, including the basins of Amazonas, Araguaia-Tocantins, Paraguai, Paraná-Prata and São Francisco rivers, which, altogether, host high fish diversity. This natural condition in combination to institutional improvements over the past three decades (Sousa; Beraldo, 2023 and Oliveira; Ummus, 2024) has made the recent spread of fish farming from Northern to Southern Brazil easier. Tambaqui (*Colossoma macroporum*), which is an Amazonian fish species, has become the most successful trade product in foreign markets, among all cultivated species. It first catered American, Canadian and Japanese consumers (Pedroza Filho; Rocha, 2024).

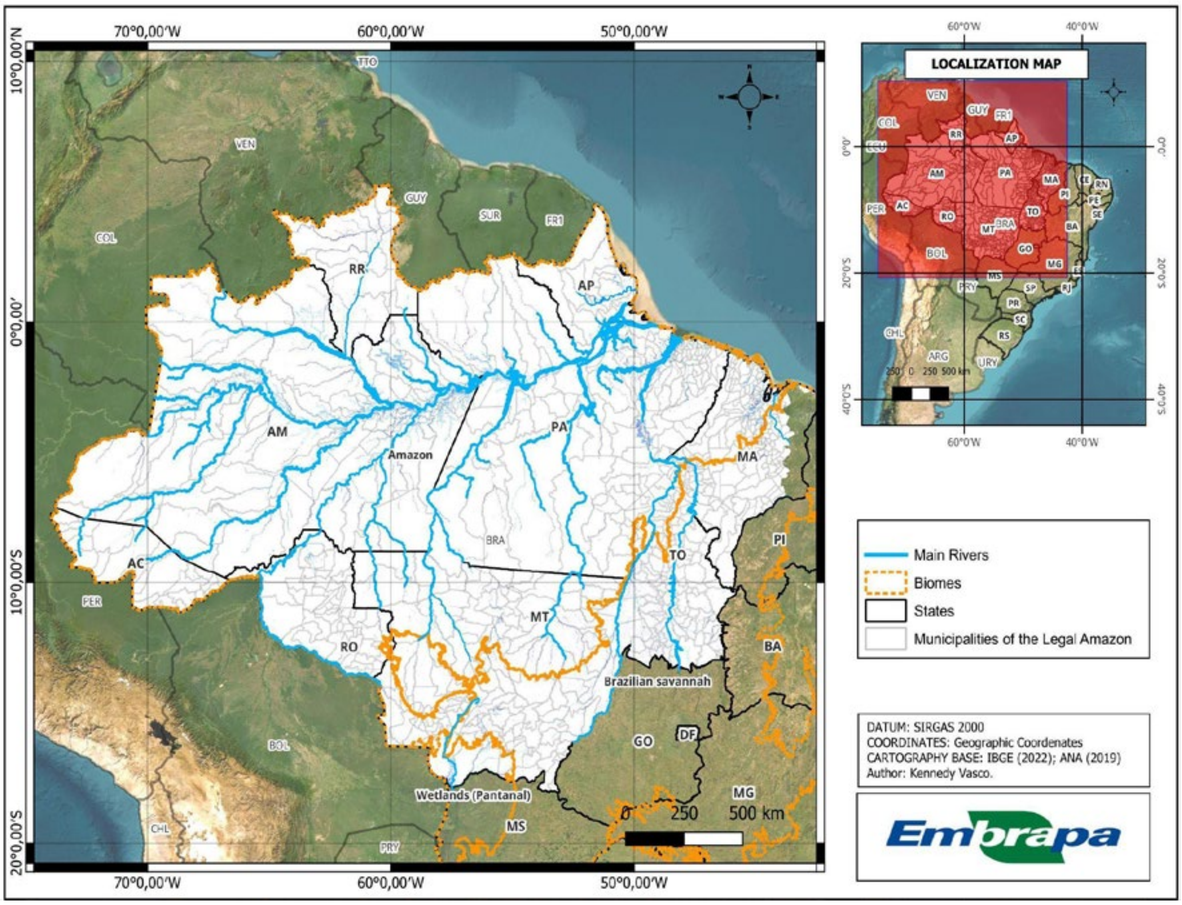
Curimatã (*Prochilodus lineatus*), matrinxã (*Brycon cephalus*), pacu (*Piaractus mesopotamicus*) and pirapitinga (*Piaractus brachypomus*) are other Brazilian fish varieties used for fish farming, mainly in fishponds. Low technological development level in comparison to non-native species, and potential to invade and cause damage, are the main issues hindering these species' expansion across the country, as observed for tambaqui, in Doce River basin (Moro *et al.*, 2013). Consequently, traditional production in Brazil, such as that of cattle ranching, poultry and hog farming, was led by highly capitalized companies and fully integrated to the global agribusiness, such as JBS, which still rules the national packaged food and meat industry sector (Hoppewell, 2016).

Although most Brazilian prefer to daily eat beef, chicken and pork, Brazilian Amazon fish are highly demanded in local markets (Moraes; Schor, 2011). This regional particularity opens room for fish farming to increase its scale and for governors to implement growth poles to face the strong competition set by other animal-protein chains. In addition, fish farming could be integrated to eco-friendly systems as alternative to cattle ranching, since it accounts for destroying biodiversity in many parts of the Amazonian biome (Hoelle, 2017).

MATERIALS AND METHODS

Municipal Livestock Survey conducted by the Brazilian Institute of Geography and Statistics (IBGE) provided statistical information about aquaculture production across different geographic dimensions. Data on fish production gathered in 2022 (the most recent data available in this public web data service), except for data on live fry, juveniles, sea and ornamental species, were extracted from this database. In total, 773 municipalities located in the Legal Amazon were selected. This spatial limit was established by the Brazilian government in the mid-20th century (Brasil, 1953). This region includes nine states from Brazil's Northern, Northeastern and Midwestern regions, namely: Acre (AC), Amapá (AP), Amazonas (AM), Maranhão (MA), Mato Grosso (MT), Pará (PA), Rondônia (RO), Roraima (RR) and Tocantins (TO). Furthermore, this region exceeds the Amazonian biome and encompasses the Brazilian savannah (Cerrado) and wetlands – Pantanal (Figure 1).

Figure 1 | Spatial location of the Legal Amazon and its main rivers



Source: Elaborated by the authors (2024). Note: The Legal Amazon is herein referred to as the Brazilian Amazon.

A significant fraction of all fish species grown in Brazilian Amazon municipalities come from Amazonian hydrological basins (i.e., Amazonas, Araguaia-Tocantins, and Paraguai rivers). Tambaqui is the most abundant species in this region, and its production accounts for approximately 100.000 tons of fish (IBGE, 2022). Tambaqui hybrids, namely: tambacu and tambatinga, rank the second position in this ranking, and they are followed by the catfish group: pintado (*Pseudoplatystoma corruscans*), cachara (*Pseudoplatystoma fasciatum*), cachapira (*Leporinus obtusidens*), pintachara (*Pseudoplatystoma spp*) and surubim (*Pseudoplatystoma fasciatum* and *P. tigrinum*). Tilapia (*Oreochromis niloticus*), which is a non-native species, ranks the fourth position in this ranking, whereas matrinxã (*Brycon brevicauda Günther*) and curimatá/curimbatá (*Prochilodus spp.*) hold the remaining positions within this ranking's top six. Table 1 summarizes the features of each selected species over this process.

Table 1 | Top six fish farming species in the Brazilian Amazon - 2022

Specie	Production in 1.000 t	Habitat
Tambaqui	97	Amazon River basin
Tambacu; tambatinga	41	Tambaqui/pacu hybrid (Paraná-Prata River basin) and pirapitinga (Araguaia-Tocantins River basin)
Pintado, cachara, cachapira, pintachara, and surubim	10	Surubim is a native catfish to Brazil and it has two varieties, namely: pintado (*Pseudoplatystoma corruscans*) (Paraná-Prata, Paraguai, and Uruguai River basin), cachara (*Pseudoplatystoma reticulatum*) (Paraná-Prata and Paraguai River basin) and cachapira/pintachara hybrids
Tilapia	4	Nilo River basin
Matrinxã	4	Amazon River and Araguaia-Tocantins River basins
Curimatá; curimbatá	3	Most Brazilian river basins

Source: Moro *et al*. (2013); IBGE (2022). Elaborated by authors. Note: Pintado, cachara, cachapira, pintachara and surubim are known as "Brazilian catfish".

Round fish, such as tambaqui, pacu, pirapitinga and their hybrids are bred in the Brazilian Amazon due to their low cost, high profit potential and market demand (Moro *et al.*, 2013). These features can be compared to those of tilapia, which is a traditional farming fish, worldwide. Native catfish, matrinxã and curimatá/curimbatá, also have trade relevance and present potential to be expanded in this region.

According to FAO (2024), the demand for aquaculture products is expected to increase in the coming years. This sector has achieved higher scale in recent years; therefore, its spatial distribution may vary in the future, a fact that points towards the implementation of poles featured by homogeneous or polarized spaces. Moran's I, or LISA (Local Indicator of Spatial Association) is the statistical model adopted to analyze this issue. This is a widely applied approach to test the spatial autocorrelation null hypothesis, mainly in studies on the food and agricultural industries (Marasteanu; Jaenicke, 2016).

The LISA model allows visualizing "clusters" of values resulting from the sum of *n* components in order to find the Global Moran's I. It is done by drawing the linear association between the variable of interest on the x-axis and the spatially weighted sum of neighboring values on the y-axis (Anselin, 1995). The plot is further divided into quadrants, based on the variables' recoded mean values and on their lagged values: low-low, low-high, high-low and high-high. Freeware GeoDa provides clear explanations and calculations of this methodology (Anselin; Rey, 2014), and that is what makes this method easily applicable in the present research context. The only task lies on both inputting data and selecting the outputs, which includes (Table 2):

Table 2 | Local Moran´s I (LISA) inputs and outputs selected in the present study

Class			Definition
Input	*x*-axis	Fish farming production	Table 1
	y-axis	Matrix of distance *w*	Binary criteria "queen"
Output	High-high	Quadrant I of linear regression	*p*-value < 0.05
	High-low	Quadrant IV of linear regression	

Source: Research results. Elaborated by the authors.

The x-axis was set by data defined in Table 1, whereas the y-axis encompassed a binary criterion (w: 1 – municipalities sharing a border; w: 0 – municipalities that do not share a border) by following the "queen" contiguity method (Anselin, 1995). The linear regression recorded for this interaction provided outputs sorted based on their association level, which was depicted in a plot. If the score was $p < 0.05$ and was located in Quadrant I, it pointed out a high-high cluster in the region. Based on this criterion, the definition of fish farming poles in the Brazilian Amazon regarded municipalities accounting for high production values capable of setting statistical-relevance spatial interactions ($p < 0.05$) with their neighbors (high-high).

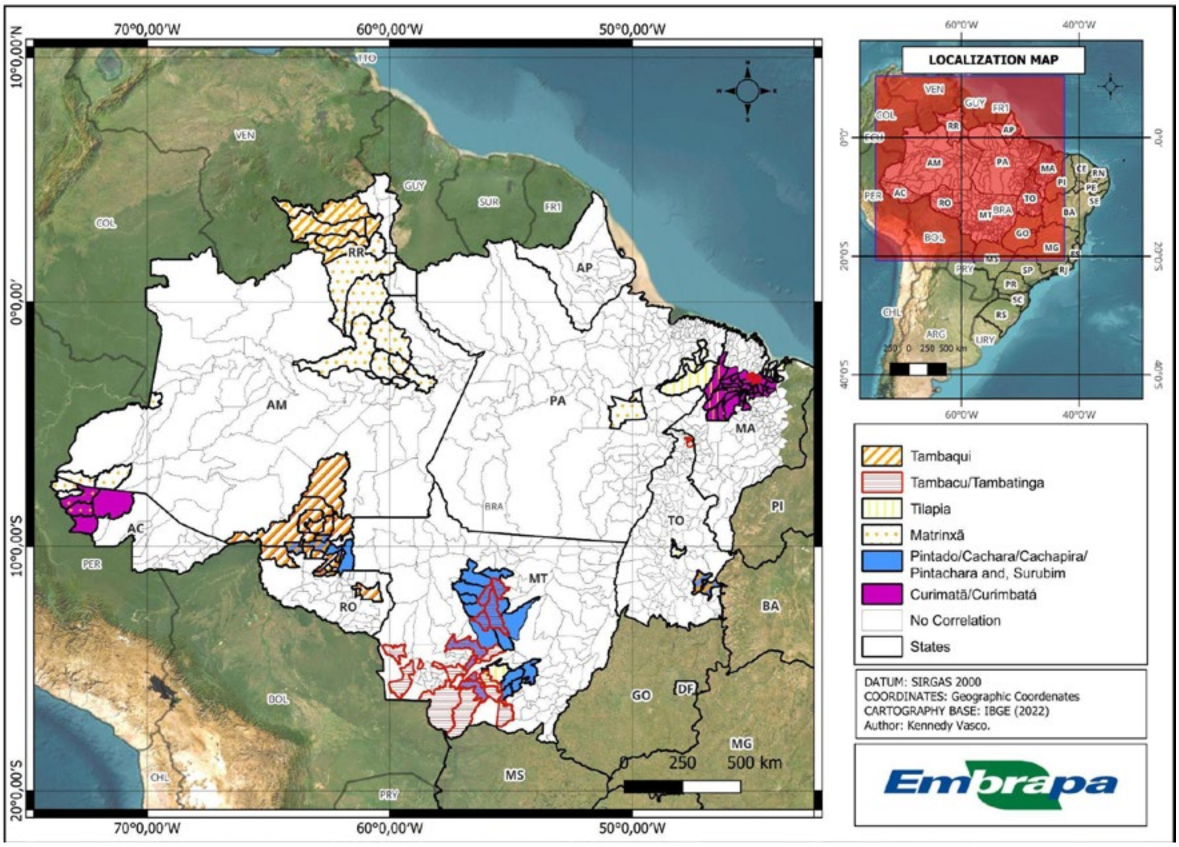
The next step concerned deepening the understanding of fish farming clusters' economic sustainability in the Brazilian Amazon. The adopted empirical approach aimed at generating the growth rate for each municipality based on the linear regression of a logarithm substantiated by municipal gathered data from 2014 to 2022 (Bueno *et al.*, 2005). The analyzed dependent variable corresponded to the intercept listed in Table 1, whereas study year (Year) was the independent variable.

Linear regression analysis was conducted in R software (R Core Team, 2024), and the “rstatix” package was applied to detect and remove outliers of each parameter. Municipalities with null, missing or fewer than 2-year data were excluded from the analysis. The short-term fish farming production forecast in Colorado do Oeste-RO, for example, would have been distorted without the exclusion of outliers and null values. This analysis’ result robustness provided a reliable basis for drawing conclusions about these clusters’ potential to progress into agro-poles, into centers capable of promoting sustainable practices through economic diversification.

RESULTS AND DISCUSSIONS

According to LISA, 169 municipalities were placed in the “high-high” quadrant, and this finding highlights their status as fish farming poles in the Brazilian Amazon (Figure 2).

Figure 2 | Spatial location of Brazilian Amazon farming fish area-poles - 2022

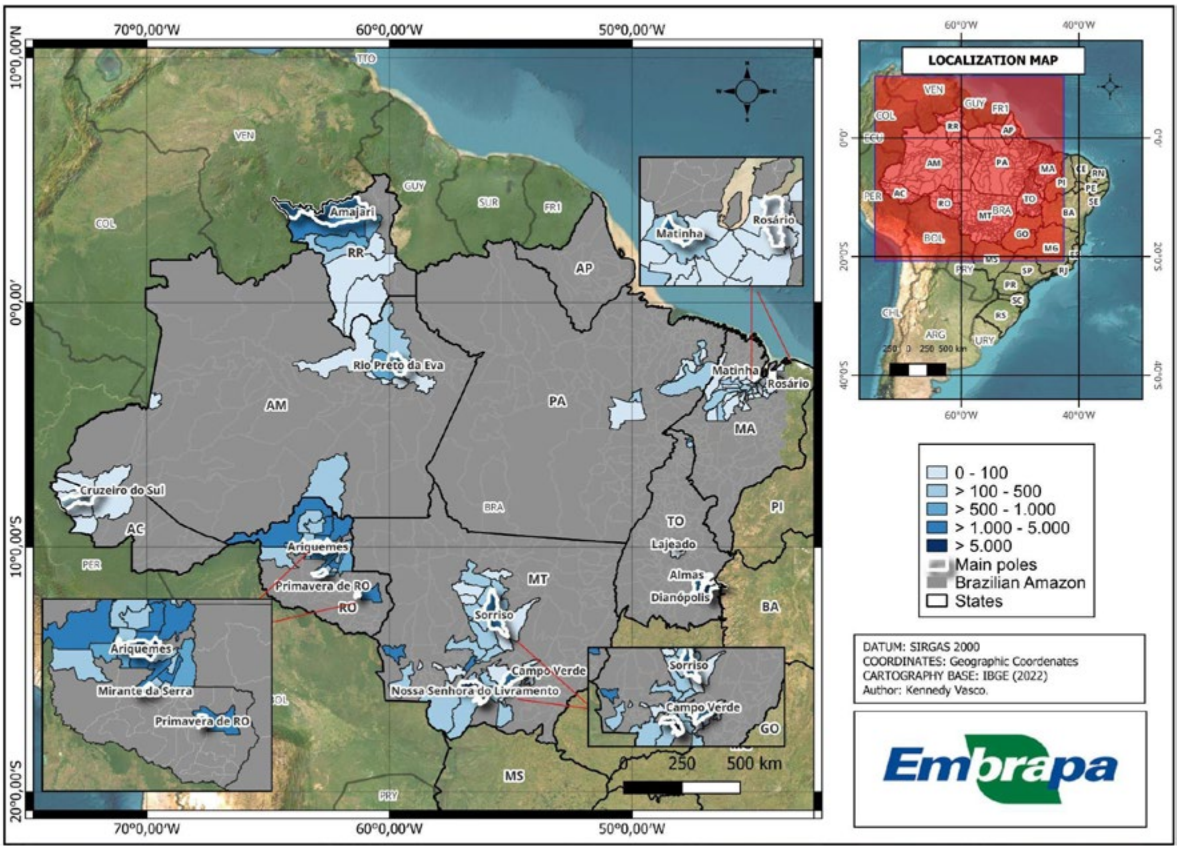


Source: Research results. Elaborated by the authors (2024).

Extensive clusters span two (Acre-Amazonas, Amazonas-Roraima and Maranhão-Pará) or even three states (Rondônia-Amazonas-Mato Grosso). Amapá is the only state lacking identified area-poles. In 2022, production between these poles ranged from 12.1 tons in Ariquemes-RO to 0.4 tons in São João Batista-MA. Notably, tambaqui production in Rondônia State, mainly around Ariquemes-RO (30 tons), tambaqui hybrids production in Mato Grosso (12.9 tons) and tambaqui production in Roraima (8.8 tons) were significant. On the other hand, tilapia production in Palmas-TO-Lajeado-TO (0.9 tons) and curimatá/curimbatá production in Acre (2 tons) emerged as this sector's smallest outputs in the region.

Tambaqui, and its hybrids, are primary fish farming sector drivers in the Brazilian Amazon. This activity's main poles are located in Ariquemes-RO (12.1 tons), Nossa Senhora do Livramento-MT (7.5 tons), Amajari-RR (4.4 tons), Primavera de Rondônia (4.0 tons), Almas-TO (3.7 tons), Sorriso-MT (1.8 tons), Matinha-MA (1.7 tons) and Mirante da Serra-RO (1.6 tons) municipalities (Figure 3).

Figure 3 | Spatial farming fish production distribution (tons) in the Brazilian Amazon poles - 2022

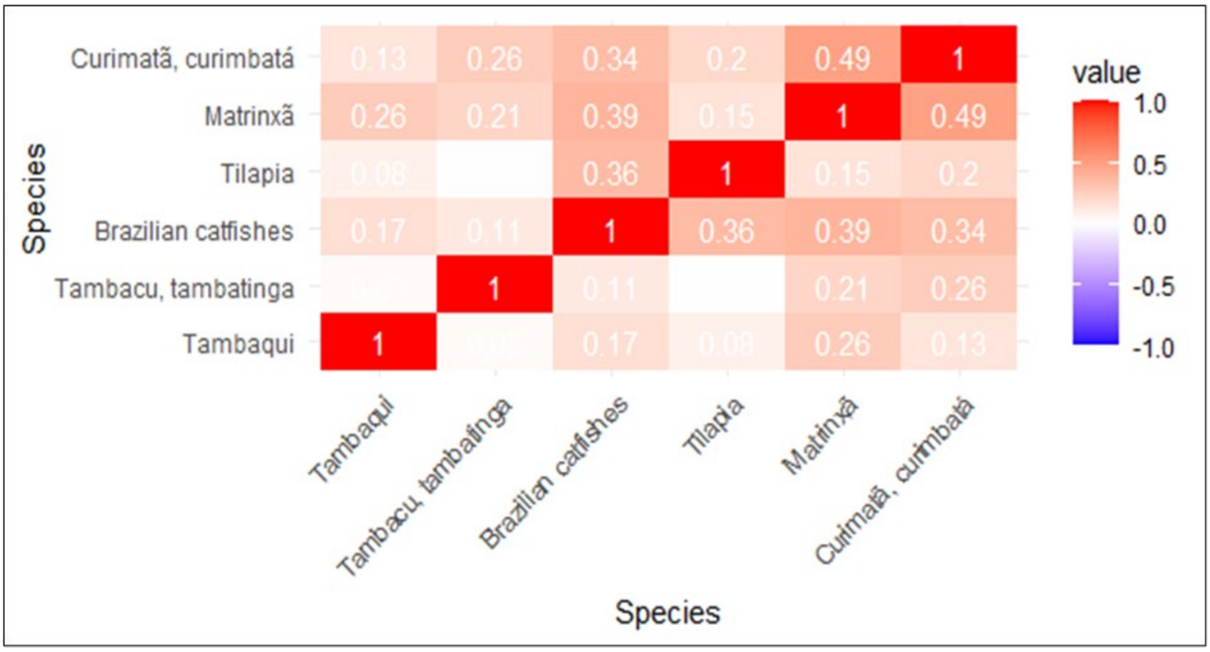


Source: Research results. Elaborated by authors (2024).

According to the spatial distribution analysis (Figure 3), there is close association between aquaculture economy and peripheral Legal Amazon municipalities. These regions show characteristic deforestation signatures and active pastureland expansion. The emerging aquaculture sector is replacing and/or coexisting with cattle grazing areas. Notably, federal highways (BR-163/174/364) intersect emerging aquaculture production clusters, and it suggests infrastructure-mediated production gains due to reduced transaction costs and improved access to the market.

Ariquemes-RO, Campo Verde-MT, and Igarapé do Meio-MA are poles tending to diversification. Fish species combination in the same area is also observed in the Acre-Amazonas intersection, where curimatã/curimbatá is bred together with matrinxã, tambaqui is bred together with matrinxã in Roraima, tambaqui, or its hybrids, are bred together with Brazilian catfish species in Rondônia and central Mato Grosso. Yet, other associations are observed in Central Maranhão and Southeastern Tocantins states. On the hand, specialization, which means breeding one single species, is observed in tilapia production areas, such as in Palmas-TO, Paragominas-PA and Chapada do Guimarães-MT. Actually, tilapia presents low correlation level to other species, and this feature is similar to that of tambaqui and its hybrids (Figure 4).

Figure 4 | Brazilian Amazon farming fish poles correlation analysis applied to each species (% growth)

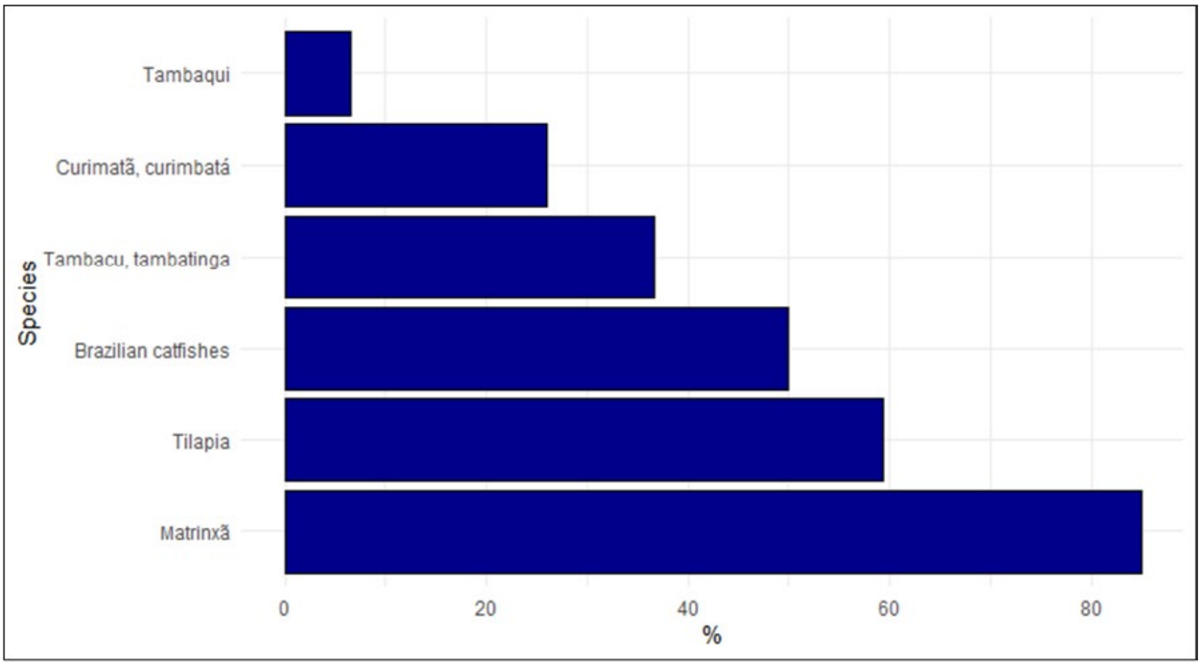


Source: Research results. Elaborated by the authors (2024). Note: Brazilian catfish: “pintado, cachara, cachapira, pintachara and surubim”; value (1 – correlation; 0 – no correlation).

Tilapia is a non-native species to the Brazilian ecosystem, and it is the reason for concern about using it in multiple farming systems. In addition, only Tocantins, Pará, Maranhão and Mato Grosso states support its breeding. The high production of tambaqui and its hybrids often marginalizes the benefits from introducing other species. Tambaqui production reached 12.1 tons in Ariquemes-RO, back in 2022, for example, whereas Brazilian catfish production only reached 1.3 tons, and this number corresponds to less than 12% of this municipality's overall production. It is crucial recalling that surubim, and other species in this same group, is piscivorous, a fact that requires extreme caution when it is managed along with other species. Finally, the matrinxã-curimatã/curimbatá (0.49) combination was the best one, as depicted in Figure 4. This last species is known for its hardiness, ease management and fast growth (Moro *et al.*, 2013), all these conditions are beneficial for multiple systems.

Regarding Matrinxã, it is recorded the highest growth rate in fish farming poles in the Brazilian Amazon between 2015 and 2022 (Figure 5).

Figure 5 | Mean growth rate recorded for each species in the Brazilian Amazon municipalities (2015-2022)



Source: Research results. Elaborated by the authors (2024). Note: Brazilian catfish are "pintado, cachara, cachapira, pintachara and surubim".

The matrinxã production thrives in Acre and Amazonas states' hinterlands, as well as in Manaus-AM region, where this species is highly valued in regional markets (Moraes; Schor, 2011). Tilapia accounted for tremendous growth in Maranhão municipalities, mainly in Bom Jardim-MA (492%). Finally, Brazilian catfish species expanded in Rondônia and Mato Grosso states, and they tend to replace tambaqui production. Similar effect is observed with its hybrids, which are more efficient in cultivation systems than "pure" tambaqui specimens. Furthermore, curimatã/curimbatá growth rate is low, although this is a complementary species in fish farming.

Finally, while new area-poles are emerging in the Brazilian Amazon, the primary ones, among them Ariquemes-RO, are prone to stability. Sorriso-MT reached its production limits and recorded negative growth for all herein analyzed fish species. Such stagnation can be explained by natural or economic constraints such as water and land availability, inadequate infrastructure to support local aquaculture expansion, institutional factors and economic crisis (Castro *et al.* 2015*;* Barbosa; Lima, 2016; Brabo, 2023 and Oliveira *et al.*, 2024).

CONCLUSION

The present study mapped the fish farming poles in the Brazilian Amazon and assessed their sustainability by applying the economic development concept used by regional sciences. Fish farming is a valuable market asset in this region, and it is expanding; however, it requires proper organization in order to enhance its competitiveness towards other industrial food sources. Municipalities accounting for high fish production are pivotal progress drivers if producers and authorities adopt reliable information to subsidize policies aimed at establishing "fish corridors" or "aquaculture extension networks" in order to strengthen producer associations and boost innovation.

Mapping "field of forces", as originally conceptualized by François Perroux, in the fish farming sector in the Brazilian Amazon was based on using Local Moran's I as assessment tool. According to the results, these are homogeneous and polarized spaces where some area-poles breed one, two or even more fish species. This diversification profile could mitigate economic risks and encourage complementary value chains that would become valuable targets for regional sustainable development policies.

Municipalities with both low and high production levels reflect varying production development and growth rate stages, as herein evidenced. States holding well-established aquaculture sectors, such as Rondônia and Roraima (driven by tambaqui production), have potential to set certain municipalities as “agropoles”. These central poles could enhance linkage effects and promote economic-ecological system projects aimed at recovering hydrological basins. It remains crucial at the time to acknowledge watersheds as this activity’s essential input. Further studies carried out in other regions are needed for better understanding their limiting factors.

Furthermore, the fish farming sector in the Brazilian Amazon faces significant challenges to achieve sustainable economic development. Implementing tilapia, or other non-native species, and tambaqui hybrids poles is a potential threat to these ecosystems’ ecological balance. It may also prevent fish farming consolidation as sustainable activity in comparison to other animal–protein sources. On the other hand, Brazil is known for its water abundance and fish resources, besides its public institutions focused on promoting sustainability policies. These factors are essential to overcome the previously mentioned limitations and to boost the fish farming sector towards sustainable development.

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