When do Supply Chains Strengthen Biological and Cultural Diversity? A New Method and Indicators for the Socio-Biodiversity Bioeconomy[1]

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Abstract

Bioeconomy has gained traction among the broader discourses of sustainable development, ecological transition, and circular economy. In the perspective promoted by governments of the Global North and international institutions, bioeconomy can lead to the gradual replacement of fossil-based raw materials and nonrenewable resources by biomass and renewable biological resources. This view has also been increasingly adopted in the Global South, but with important variations to address the specificities of mega-biodiverse regions. In these regions, bioeconomy must encourage activities that protect ecological biodiversity and strengthen local communities, promoting their well-being and cultural diversity. The present paper designs methods and explores indicators for the analysis of the bioeconomy in this socio-biodiversity perspective. Based on a field study in the state of Amazonas (Brazil) and interviews with relevant actors of supply chains in the Amazon region, we present a methodology proposal for mapping and evaluating bioeconomy value chains for consistency with the principles of socio-biodiversity. Applying a bottom-up approach that takes into account the perspective of the individuals and communities involved in the evaluation, the proposal intends to capture relevant aspects of socio-biodiversity, such as qualitative aspects of production chains, specific territorial dynamics, and the broader institutional context of the bioeconomy. A case study of the *pirarucu* (*arapaima gigas*) value chain in the Amazon shows the potential of the proposal to inform public policies related to the bioeconomy in the region.

Keywords: Methods; Evaluating metrics; Supply chains; Socio-biodiversity; Bioeconomy.

1. Introduction

Bioeconomy has been attracting growing attention as an alternative path to face the environmental challenges of the twenty-first century. Recent literature presents pathways for a sustainable and decarbonized economy development founded on the use of biomass and renewable natural resources (Bugge et al., 2016; Vivien et al., 2019; Giampietro, 2019). The term "bioeconomy" is controversial, however, and used with several different meanings. Specific challenges in the Global South – especially in mega-biodiverse regions – have been fostering reflection on social, cultural, and local biodiversity issues (Ortega-Pacheco et al., 2018; Rodríguez et al., 2019; Nobre and Nobre, 2019; Abramovay et al., 2021; Costa et al., 2022). This emerging socio-biodiversity bioeconomy still lacks a systematized and consistent analysis framework.

[1] Versão preliminar. Não divulgar e citar sem o consentimento dos autores.

In this paper, we design a method for the analysis and diagnosis of biodiversity chains, aiming to assess and evaluate paths and obstacles to achieving the targets of the socio-biodiversity bioeconomy, and to inform public policy. The remainder of the paper is organized as follows. Section 2 discusses the theoretical framework, highlighting the three separate bioeconomy strands and the different methods and indicators employed by each of them. Section 3 presents how the method and indicators for analyzing socio-biodiversity bioeconomy value chains were chosen and developed. The methodology proposed is discussed in Section 4, along with its application to a pirarucu value chain (*arapaima gigas*) in the Amazon Region (Brazil). Section 5 summarizes our main contributions and limitations, both methodological and in relation to the case study.

2. Bioeconomy concepts and perspectives

2.1 Economic-ecological bioeconomy: a biophysical view of the economy

In the 1970s, Nicholas Georgescu-Roegen (1971) advocated for a revolution in economic theory, so it would consider biophysical aspects of the economic process. In biophysical terms, an economy does not create energy or matter, but rather transforms resources extracted from nature, dissipating energy and generating polluting waste. Initially, the term “bioeconomics” has been employed to designate a new scientific paradigm to replace neoclassical economics, in which the economy was considered as part of nature. Subsequently, “bioeconomy” was used to refer to political and technological recommendations connected to the theoretical contributions and to Georgescu-Roegen’s “minimum bioeconomic programme” (Vivien et al., 2019; Giampietro, 2019).

Those recommendations are based on the entropic vision of bioeconomics and, more recently, of ecological economics. Like any living being, the economic process depends on the input of low entropy matter and energy and on the output of degraded matter and heat to keep itself organized. It is a metabolic view of the economy. Technology may improve the economy's environmental efficiency but does not eliminate the dependence on new natural resources input. The alternative is to meet humanity's needs with minimum natural resources depletion and energy consumption, at least until solar energy use becomes viable and widespread (Georgescu-Roegen, 1975).

Methods developed based on this bioeconomy perspective seek to generate indicators that represent socio-economic metabolism, accounting for material flows and stocks of economic systems (their physical quantity in tons), as well as the energy associated with economics transformations (Gerber and Scheidel, 2018; Giampietro et al., 2009; Fischer-Kowalski, 1998). Technological change and development throughout history are characterized by transformations of countries' socio-metabolic profiles and, occasionally, by transitions to different socio-ecological regimes (Krausmann et al., 2008; Fischer-Kowalski and Haberl, 2007).

2.2 Mainstream bioeconomy: economic use of biological resources

Mainstream bioeconomy originated in the wake of the biotechnological revolution in the 1990s. Advances in genetic engineering were to revolutionize fields like pharmaceutics, medicine, agronomy and chemistry, generating wealth and jobs. The concern with environmental benefits was initially not at the core of policy discussions and strategies (Bugge et al., 2016; Patermann and Aguilar, 2018; Vivien et al., 2019; Bröring et al., 2020).

In the last decade, this view became associated with energetic transition and decarbonization of economies, and has been incorporated into the mainstream policy by institutions like the Organisation for Economic Co-operation and Development, the European Union and several national governments (OECD, 2009; EU, 2018; Philp and Winickoff, 2019). In this framework, bioeconomy may be defined as the set of economic activities connected to the invention, development, production, and use of renewable biological resources (OECD, 2009). Bioeconomy would lead to the progressive substitution of fossil-based raw materials and nonrenewable resources, and to circular production methods, optimizing and recycling natural resources in productive processes (EU, 2012; EU, 2018; Bugge et al., 2016). This new focus on technologies and production systems based on biomass as substitutes for fossil fuels enables the bioeconomy to encompass a broad range of economic activities, far beyond biotechnology. It also makes it potentially the foundation of many sectors, including agriculture, forestry, fisheries, commerce, waste management, and several industries (Keegan et al., 2013; McCormick and Kautto, 2013; Philp and Winickoff, 2019).

Analytical methods associated with this perspective aim to quantify and qualify the environmental sustainability of production chains, or alternatively its ability to create wealth and jobs. Life cycle analysis (LCA) is one of the most used methods to assess environmental performance (Cristóbal et al., 2016; Karvonen et al., 2017; D'Amato et al., 2020; Talwar et al., 2022). LCA quantifies environmental impacts, from resource extraction to the end of product life, as well as the changes that would result from a transition to a new system. This analysis can inform decision-making during the transition to a circular bioeconomy (Sevigné-Itoiz et al., 2021).

Regarding economic potential, several methods and models are used to calculate the size of the bioeconomy of countries or regions. The most common ones are: gross value added (GVA), input-output (I-O) analysis and computable general equilibrium (CGE) models (NAS, 2020). There are estimates for several countries, especially in the Global North (Wesseler and von Braun, 2017; D'Adamo et al., 2020). In the US, for instance, NAS (2020) has estimated that bioeconomy accounted for around 5% of the country's gross domestic product (GDP) in 2016. In Germany, bioeconomy's value added reached 7.6% of GDP in 2007 (Efken et al., 2012), a share close to that in the Netherlands (6.6–7.2%) between 2008 and 2012 (Heijman, 2016).

2.3 Socio-biodiversity bioeconomy: cultural and natural richness of "poor" regions

A third, more recent, perspective on bioeconomy has emerged in mega-biodiverse countries of the Global South (Ortega-Pacheco et al., 2018; Rodríguez et al., 2019; Nobre and Nobre, 2019; Abramovay et al., 2021; Costa et al., 2022). The first distinctive trait of this bioeconomy lays precisely in its emphasis on biodiversity. Second, the recognition of the populations living in those regions, whose lives and livelihoods depend on nature and biodiversity conservation, and are threatened by destructive economic activities. Knowledge and culture of the indigenous, fishermen and fisherwomen, riverside and peasant populations living in mega-diverse regions must be taken into account in order to constitute the basis for bioeconomy development.

Among the mega-biodiverse regions, the Amazon region with its huge biological diversity and relevance to climate regulation stands out in the debate on socio-biodiverse bioeconomy (Abramovay et al., 2021; Costa et al., 2022; WTT&COI, 2022). Bergamo et al. (2022) propose four principles for a bioeconomy in the Amazon: i) zero deforestation; ii) diversification of production methods; iii) strengthening of ancient practices of the region; and iv) equitable distribution of benefits. Amazon State in Brazil has adopted similar principles: i) biodiversity conservation; ii) science and technology (S&T) serving the sustainable use of socio-biodiversity; iii) reduction of social and territorial inequality; and iv) expansion of forested biodiverse and sustainable areas (Amazonas, 2021, p.1).

Socio-biodiversity bioeconomy contrasts with the mainstream perspective for both its emphasis on people and its foundation on biodiversity. A bioeconomy based on the use of renewable biological resources, though may contribute to greenhouse gas emissions mitigation and to energy transition, does not necessarily ensure biodiversity conservation. For instance, bioeconomy based on biofuels or forest monocultures are generally harmful to biodiversity (Pfau et al., 2014; Bugge et al., 2016; Hurmekoski et al. 2019; Piplani and Smith-Hall, 2021), and therefore counter-productive in mega-biodiverse regions. In those regions, socio-biodiverse economies should be based on value chains that respect ecosystem resilience and on environmental functions that sustain biodiversity.

Regarding social aspects, socio-biodiversity bioeconomy carries more complexity than the other perspectives, as it responds to important territorial and social challenges, and specificities which characterize many mega-diverse regions of the Global South. Local populations, indigenous, traditional communities in the Amazon are often vulnerable to the violence of groups practicing illegal actions, such as land invasion, mineral and timber exploitation. In those cases, more than generating wealth, bioeconomy shall foster activities that preserve the forest and protect biodiversity, while empowering local communities and securing their well-being (Becker and Stenner, 2008; Abramovay et al., 2021; Costa et al., 2022; WTT&COI, 2022; Bergamo et al., 2022). At the same time, these populations and social movements are considered protagonists because they have local, which are necessary for scientific and technological advancements connected to biodiversity. Empowerment of local populations enables decision-making and actions for improving the bioeconomy, even in resource-constrained contexts (UNSDN, 2012; Petesque, 2020; Laven, 2009).

In contrast to previous perspectives, socio-biodiversity bioeconomy is based on concrete experiences and activities conducted by populations living in mega-biodiverse regions. There is a consolidated literature on such activities connected to socio-biodiversity, particularly on non-timber forest products (NTFPs). Several case studies analyze whether NTFPs bring about development or improvements for local communities without overloading forest resources or ecosystems, with mixed results (Arnold and Pérez, 2001; Belcher et al., 2005; De Mello et al. 2020). These empirical results are often ignored by proponents of the socio-biodiversity economy, which has a more normative character when proposing a new economic model, despite not yet having delineated clear paths to overcome the social and environmental challenges identified in the literature.

3. Methods

This article is a result of the Brazilian "Bioeconomy Project – Bioeconomy Value Chains Analysis in Amazonas and São Paulo States"[2], dedicated to the analysis of value chains based on biodiversity in Amazonas State with consumption potential in São Paulo. The quest for

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methods to systematically and rigorously analyze socio-biodiversity bioeconomy proved challenging and motivated this research. With the objective of substantiating recommendations for public policy based on an understanding of the factors hindering and fostering biodiversity value chains in the Amazon, we noted an abundance of studies on the region – particularly on NTFPs – but not based on bioeconomy's perspectives. On the other hand, bioeconomy literature focused on methods skewed to the Global North. Understanding the social and cultural issues typical for the Global South seemed to require a more qualitative analysis of value chains and thus a more appropriate methodology.

The first step towards methodological routes consistent with socio-biodiversity bioeconomy was to consider the social and cultural specificities of the various territorial contexts in the Amazon region (e.g., relevant species in each territory, level of environmental degradation, types of extractive activities carried out by communities and compatible with their way of life, existence of conflicts and threats to people and the environment). In order to focus on the socio-environmental and economic criteria compatible with bioeconomy targets, the method had to capture local indicators and values. These criterias for analyzing socio-biodiversity bioeconomy chains were identified in interviews with actors in the chains of pirarucu, açaí, cocoa, and Brazil nuts in the Amazon, specifically in the Amazonas State (Brazil). From March 2021 until August 2022, 22 semi-structured interviews lasting 45-120 minutes were conducted with members of producer associations, researchers and staff of research institutes, social organizations and the public sector interacting with producers, actors in other chain links like middlemen, processors, buyers, a tannery and a restaurant (Appendix A). Finally, in June 2022 field research was conducted in the Mamirauá Sustainable Development Reserve (Amazonas), where we took part in the assembly of the Federation of Pirarucu Management Fishermen and Fisherwomen of Mamirauá (FEMAMPAM, acronym in Portuguese) and applied face-to-face questionnaires to 31 pirarucu fishermen and fisherwomen. Each interview took between 30 and 120 minutes.

Based on the priorities and specificities identified in interviews and field research, we performed a critical assessment of traditional value chain analysis, focusing on economics skewed towards competitiveness (Davis and Goldberg, 1957). In order to deal with critical aspects like value distribution among production chain segments, governance and environmental impacts over time, we considered approaches to value chain upgrading (Gereffi, 2019; Gereffi and Lee, 2016; Gereffi et al., 2005; Humphrey and Schmitz, 2004) and polycentric governance (Ostrom, 2010; Ostrom et al., 2012). Building on the intersection of these theoretical perspectives with research analyses, we present a proposal for mapping and for evaluation metrics of value chains, consonant with socio-biodiversity bioeconomy principles. Our proposal was ultimately tested in a case study on the Amazon pirarucu value chain.

4. Results

4.1 Proposal for the Analysis of Socio-biodiversity Bioeconomy Value Chains

The first challenge for adequately mapping and assessing socio-biodiversity bioeconomy value chains lies in diverse, sometimes conflicting objectives and the multiple criteria that emerge from the community. Testimonials by actors have shown that socio-biodiverse chains in the Amazon cannot aim only at short term efficiency and enhancing job, income generation or equitable market access. It is paramount that these go hand in hand with ecosystem resilience and the conservation of biological and cultural diversity. For instance, value chains like palm oil, açaí, coffee or cocoa can either promote or be counterproductive for biological and cultural diversity, especially by encouraging monoculture and compromising the autonomy of communities (Freitas et al., 2021). A qualitative assessment of socio-biodiversity bioeconomy chains is important to bring up inconsistencies and potential incompatibilities of potential bioeconomies.

Indicators used to analyze value chains in general are not based on the perspective of producers or local population (Neves et al., 2020; Farina and Zylbersztajn, 1998; Saes and Silveira, 2014, Neven, 2014). By incorporating the participation of local actors in the construction of indicators through citizen science (Tourneau & Canto, 2019), criteria can be expanded to address qualitative aspects connected to human well-being and broad environmental issues. Both science and technology can be instruments aligned with traditional knowledge and relevant not only for the economic use of natural resources, but also for environmental conservation and fostering the well-being of local populations. Take advantage of markets to improving the quality of life of communities require solutions adapted and validated by communities according to the territoriality (Becher, 2010; Bröring et al., 2020; McCormick & Kautto, 2013; Du Plessis & Brandon, 2015; Abramovay et al., 2021; Azevedo-Ramos et al., 2020, Lovejoy & Nobre, 2019). The criteria and indicators should provide information for both the vertical and horizontal perspectives, considering the concept of productive knowledge networks (De Oliveira Moraes & Schor, 2021). Through the integration between such axes – horizontal and vertical – it is possible to understand the specificities of the interaction between the different forestry products and their territories.

Finally, socio-biodiversity bioeconomy chains are embedded in broader institutional contexts, in which operate both formal and informal rules (see North, 1990; Ostrom et al, 2012). Interviews with local actors have revealed the decisive role of institutions such as community associations and social organizations in value chains. In many cases, polycentric governance experiences can be more successful in managing common-pool resources than cooperation arrangements. That is why it is important to listen and understand how communities act in each case (Cox et al., 2010; Ostrom et al, 2012). Likewise, governmental institutions can be determinant for the bioeconomy, by promoting inclusive and participative policies skewed towards local communities and incorporating traditional knowledge into policies and technological innovations. Socio-biodiversity bioeconomy value chains analysis must enable a deep understanding of relationships across levels: macro- (regulation), meso- (implementation), and micro- (coordination of production arrangements), enabling the identification of bottlenecks in each level and the determining factors for value distribution throughout the chain (Ménard & Shirley, 2018).

4.1.1 Value Chain Mapping

Traditional and mainstream value chain studies, which were developed at the Harvard School (Davis and Goldberg, 1957) based on economic theories such as industrial organizations, transaction costs, and resource-based theory, deal with the operational efficiency of the production system as a whole. The chain's function is to serve consumers in a way that they receive, simultaneously, lower cost and higher quality products. More competitive value chains are the ones that have higher capacity to stretch productivity boundaries, which is the sum of all best practices at a given point in time. Productivity boundaries, therefore, are constantly shifted as new technologies and practices (process, product, and organization) are developed and new inputs become available.

Nonetheless, inefficiency reduction or supply growth while prices decrease often do not mean reduced inequality in income distribution throughout the value chain segments, nor improved environmental sustainability. On the contrary, income distribution and environmental preservation are generally seen much more as restrictions than as opportunities – imposed, for instance, as regulations by legislative bodies. Rarely, the development of a strategic subsystem is seen as an opportunity for capturing value, such as a brand that builds on specific attributes – like organic, animal friendly etc. In those cases, performance indicators evaluate market share *ex post*, considering cost, productivity, and pricing strategy according to product differentiation (Neves et al., 2020; Farina and Zylbersztajn, 1998; Saes and Silveira, 2014). Even then, a focus on competitiveness -needed in order to evaluate a chain's capacity to thrive in the market and prospects for the future- imposes a vision of maximizing output in the short term, disregarding limits and socio-environmental risks of economic exploitation in the long run.

Therefore, traditional value chain studies, focused on efficiency and competitiveness, can only contribute to bioeconomy analysis if it is extended to identify factors for value chain development and adapted to assess ecological and distributional results. Figure 1 presents our proposal to analyze socio-biodiversity bioeconomy value chains, detailing the stages of the chain, the production flow (gray arrows) and the income flow (orange arrows). The orange arrows denote the sense of the analysis. While in the traditional analysis the objective was to propose competitive improvements in the food system aiming at reducing prices for consumers or increasing their benefits (gray arrows), here the main focus is to raise the economic and social benefits for communities, respecting ecosystem limits. In each box we exemplify factors that can be evaluated and suggest relevant questions to the chain analysis. This analytical toolkit can be deployed at three levels:

<insert Figure 1>

(i) Value chain - design and description*:* the first level regards (1.1) the characteristics linked to territoriality and identity of communities and (1.2) how the value chain is configured and chain actors relate to one another, considering: (a) social and cultural norms and values characteristic of the community and collective action that influence the way the chain is organized in that territory; that is, the locality-specific common property management practices. (b) competition (e.g. actors and organizations involved, size of each production segment in the relevant market, growth strategies and competition patterns or strategic groups, and product physical attributes such as perishability, consumption frequency and substitutes); (c) technology (i.e. conceptual matrix in which specific technological solutions are developed); (d) market transactions (e.g. relationships among productive segments, their actors and objectives, the leading actor or chain segment; the various degrees of dependence according to actors strategies).

(ii) Institutional governance: the second level scrutinizes governance arrangements, i.e. the rules of the game at the macro and meso-levels. At the macro-level it considers formal institutions including rules and pertaining legislation, as well as informal and cultural rules which condition the management of the value chain in the territory and may enable or restrict immaterial infrastructure development, like certification and labeling, branding and declaration of origin. The meso-level regards how organizations implement rules – public, private, and related to collective action governance (public/collective goods provision). It also ponders to what extent the rules of the game and their implementation, monitoring and inspection by public and private organizations favor the bioeconomy.

(iii) General context: this level identifies factors linked to the supply and demand for goods and services which favor or hinder the development of bioeconomy value chains. Exogenous trends are identified to analyze demand shifts like food market globalization/internationalization, dietary and lifestyle changes, animal welfare, environment/climate change as well as basic supply conditions (infrastructure, logistics, storage, credit/financing, connectivity and access to digital services, know-how, natural resources).

4.1.2. Value chain evaluation: matching metrics to objectives

Besides the value chain mapping, metrics are crucial to assess the coherence of the chain with the socio-biodiversity bioeconomy. The proposed evaluation is based on the concept of upgrading developed by Gereffi et al. (2005), Gereffi et al. (2016), Gereffi (2019), Humphrey and Schmitz (2004), and Barrientos et al. (2011). Upgrading refers to increasing the economic, social, and environmental value generated by a chain while benefiting all stakeholders. For each dimension of upgrading - economic, social, and environmental -, metrics must be adapted and broadened to reflect concerns and perspectives of local communities as well as territorial dynamics.

Economic upgrading reflects productivity gains, price improvements for producers and more equitable gain sharing throughout the value chain. It leads to improvements of: i) products, when moving towards more sophisticated product lines; ii) process, by achieving a more efficient transformation of inputs into products through superior technology or better organization; iii) product/service functionality, adding new uses to a product; and iv) chain architecture, turning relations among agents more efficient, i.e. reducing transaction cost. Social upgrading improves incomes and employment, empowers individuals and communities and enhances their autonomy (Rossi, 2013; Humphrey and Schmitz, 2004; Barrientos et al., 2011). Finally, environmental upgrading reflects environmental performance and traces changes in technology or social and organizational processes which prevent or minimize impacts and strengthen environmental services and biodiversity.

The choice, definition and interpretation of indicators may benefit from Elinor Ostrom's insights into the governance of the commons. According to Ostrom et al. (2012) and Ostrom

(2010) polycentric governance reinforces the resilience of eco-systemic services by providing: (i) opportunities for learning and experimenting; (ii) ample stakeholder participation, mobilizing traditional and local knowledge; and (iii) diversity, minimizing and/or correcting errors in decision-making. Indicators should thus reflect communities' priorities and perceptions, and allow for community monitoring along value chain development. It is paramount to count on the participation of populations and chain actors to select actions aimed at strengthening socio-biodiversity and at other social goals defined according to the territory.

Table 1 presents the socio-biodiversity bioeconomy targets and potential evaluation criteria to analyze bioeconomy value chains. Indicators are supposed to be adapted according to local settings. It is important to note that the bioeconomy value chain can upgrade the entry locality (territorial scale) or only those who participate in the value chain. Several information may depend on field work and interviews with value chain actors.

<insert Table 1>

4.2. Pirarucu Value Chain in the Amazon

The participatory pirarucu management in the Mamirauá Sustainable Development Reserve – RDSM [in the Portuguese acronym], Amazonas (Brazil)[3], is an emblematic case for the Amazonian socio-biodiversity bioeconomy, as it seizes economic and nutritional potential while conserving the environment and enabling active community participation to generate income and improve well-being.

i) Value chain structure

Figure 2 presents the RDSM pirarucu value chain, including key actors and relations among agents. The design of the value chain was mapped based on documents from the Instituto de Desenvolvimento Sustentável Mamirauá (see, Gonçalves et al. 2018), and interviews with local actors (Field research, 2020).

The pirarucu fishing involves a series of activities: monitoring of lakes all year round, to curb invaders who practice illegal fishing; plan the fishing schedule, i.e., counting the fish in the lake in order to decide the number of fish to be caught and how the income will be distributed that year; organization and carrying out of fishing (catching and cleaning the fish,

[3] Sustainable Development Reserve (SDR) is defined as a natural area that houses traditional communities, whose existence is based on sustainable systems for natural resources use. RDSM was created by Amazonas Government, on July 16th, 1996.

preparing food for the team, etc.). Fish processing is carried out partly by the fishermen's association and partly by slaughterhouses that buy fresh fish. The fish is distributed through different channels such as local fairs, restaurants, hotels, as well as local and regional distributors and the tannery that purchases the pirarucu leather. Finally, consumption is mainly restricted to the local market. The chain is supported by a set of meso-institutions - public and non-governmental organizations - that help the fishermen and fisherwomen organize collective actions, provide training, and seeks to enable their access to markets with better prices.

< insert Figure 2>

Two points were highlighted in the chain mapping: i. the collective actions of fishermen and fisherwomen in organizing fishing supported by non-governmental organizations, which also play a prominent role in improving pirarucu trade; ii. the absence of public power, with the communities responsible for watching over the lakes to prevent illegal fishing, which represents about 50% of fishing operating costs. These costs are important for communities' perception of fishing gains - 74.2% stated that their income was low, and the activities cost were high.

ii) Institutional governance

Three key regulations condition the institutional environment in which the pirarucu value chain is embedded: (a) the establishment of environmental conservation units in the Amazonas State (Decree no. 12,836, on March 9, 1990), regulating human activity to ensure sustainable exploitation; (b) the imposition of the closure period (*defeso*), during which capture, commercialization, and transportation are prohibited (IBAMA Ordinance no. 480, on March 4, 1991, updated by NI IBAMA no. 34/2004). During the closure, fishermen and fisherwomen are eligible for a monthly income from insurance; (c) criteria and procedures for pirarucu fishing in protected areas (NI IBAMA no. 01/2005). Beyond state regulation, an array of formal and informal rules has been created by local communities that participate in participatory pirarucu management and enforced through collective action. We highlight fishery agreements that regulate the use of fishing resources as defined by community members (such as quantities that can be fished, equipment allowed, number of vessels authorized to be simultaneously on the lake and fishing period, among other criteria), including measures and sanctions to be taken against violators.

Interviews showed that meso-institutions support the implementation of macro-institutional rules, by creating incentives, enforcement or monitoring. The organizations standing out are: (i) the Mamirauá Sustainable Development Institute [IDSM, Portuguese acronym], which translate general rules, protocols and government policies, such as fishery agreements, into specific guidelines adapted to local contexts, aiming to to make them more effective; (ii) the Sustainable Amazon Foundation [FAS], which coordinates the activity of local actors, filling institutional voids created by the State, and helps to improve commercialization infrastructure; and (iii) the Association of Residents and Users of SDR Mamirauá Antonio Martins [Amurmam], representing local dwellers before governmental, environmental, landholding, and legal institutions. The Association defends the rights of communities and organizes decision-making in fishing management, and also plays a key role in overseeing contractual relationships through formal and informal control mechanisms and sanctions in case of non-compliance.

iii) General Context

Pirarucu fish is part of the traditional diet in northern Brazil, but also consumed in other Brazilian regions and international markets. In the 1960s and 1970s, the expansion of the fishing fleet and ice factories, stimulated by government policies, led to overfishing (Gonçalves et al., 2018). As reproduction did not keep up with capture, pirarucu was classified an endangered species in 1976. Since then, regulatory measures, such as closures of fisheries for six months every year (October to March), and fishing management in reserve areas were put in place aiming at sustainable exploitation (CONAB, 2020).

The Mamirauá Sustainable Development Reserve was the first to implement sustainable management in Amazonas State. The policy had a clear effect: from 1999 to 2017 fish stocks grew by 427%, and the number of fishermen and fisherwomen who joined management projects jumped from 42 to 1,590. In 2017, pirarucu fishing generated an average gross per fishermen income of R$1,739.38 (US$536.85) per year, with individual values reaching up to R$6,533.70 (US$2016.57), with each fishermen ou fisherwomen working directly in fishing for a maximum of 50 days throughout the year. In comparison, the Brazilian minimum wage at the time was R$973.00 (US$289.20) per month (Gonçalves, 2018, p.88).

Nevertheless, communities still face several bottlenecks: infrastructure (logistics, fish transport, processing, distance from ice factories), financing (in the purchase of boats and fishing gear), trade (dependence on few channels and, given the high perishability of the product, prices are lower than in larger regional markets, with the exception of sales carried out through NGOs, such as FAS), bureaucracy (documentation for sale), segurança (lake surveillance). These are partially due to institutional voids left by the State, which contrast with the resolute action by meso-institutions and collective action of communities.

iv) Process, Impact, and Results Indicators

In order to assess coherence with the objectives of socio-biodiversity bioeconomy, Table 2 presents indicators for the social, economic, and environmental dimensions, including several indicators built based on the local communities' priorities and concerns. Despite the bottlenecks found in the context analysis, indicators show that the value chain has evolved over the years, with some upgrading in all three dimensions: social, economic, and environmental.

< insert table 2>

By including women in the production process, participatory fisheries management has improved gender equality in the region. Collective actions reinforce the role of fishermen and fisherwomen in performing all the tasks related to fishing and commercialization, and participating in the decision-making process. Moreover, fisheries management has not only improved supply of pirarucu in the region, but also contributed to the conservation of lakes and other species, as evidenced by strong increases in fish stocks and very low deforestation.

Meso-institutions have enabled the internalization of innovation such as training and improved infrastructure for processing and commercialization, contributing to production cost more compatible with prices. This is reflected in the relative improvement in income and well-being of communities, albeit timid in several indicators, which suggest room for additional economic and social upgrading.

5. Concluding Discussion

Our results show that the assessment of socio-biodiversity bioeconomy may benefit from indicators that take into account the perspective of the individuals and communities, and from qualitative evaluation of bioeconomy value chains. Based on this assessment, the participatory pirarucu management in the RDSM has proved to be a successful case of bioeconomy, which is in line with positive outcomes reported in previous studies focused on pirarucu management in the Amazon (Campos-Silva and Peres, 2016, Freitas et al., 2020, Campos-Silva et al., 2021, Gamarra et al., 2022). The measured impacts reflected the generally positive communities' perception about the fisheries management, although several social and economic issues are yet to be upgraded. We highlight the local income as a negative aspect; in most cases, it is just a small complement to family's income and often considered insufficient. Regarding the positive environmental and social outcomes, the analysis of the broader institutional context was found to be important in accessing key drivers of the pirarucu bioeconomy such as the role of meso-institutions. To point out opportunities and challenges related to the socio-biodiversity bioeconomy, we close this article by discussing some implications of our results.

The value chain mapping indicates that meso-institutions may organize and aggregate local actors in contexts with social and regional disarticulation, as in many socio-biodiverse regions located in the Global South. The literature has shown that polycentric institutions can have a positive role in the governance of common-pool resources when fostering innovativeness, learning, levels of cooperation of participants, and the achievement of more equitable and sustainable results (Ostrom, 2010, Ostrom et al., 2012). In the participatory pirarucu management, by increasing transparency and fairness of production chains and enhancing existing self-organizing initiatives, public and non-governmental organizations changed the dynamics of socio-biodiversity chains, creating conditions for the bioeconomy to flourish. These organizations counted on ample community participation, probably contributing to strengthening economic alternatives adapted to the communities environmental and cultural contexts. This finding is consistent with the evidence that local settings and active participation of local communities are important to successful outcomes in the management of common-pool resources (Ostrom, 2010, Cox et al., 2015).

Still, the negative economic outcomes in the pirarucu chain contrasts with the bioeconomy's focus on win-win solutions and synergies between sustainability and economy, which is emphasized in both mainstream and socio-biodiversity bioeconomies (Vivien et al., 2019; Giampietro, 2019, Nobre and Nobre, 2019, Amazonas, 2021). The vast literature on non-timber forest products, including several studies in the Amazon, also challenges this emphasis on synergies by showing that NTFP commercialization often implies a trade-off between environmental conservation and economic development (Arnold and Pérez, 2001, Belcher et al., 2005, Ros-Tonen and Wiersum, 2005, Kusters, 2009, Brites and Morsello, 2016, De Mello et al., 2020, Freitas et al., 2021). Possible pathways towards the socio-biodiversity bioeconomy should respond to these ambiguous results, providing a more realistic view of social and environmental challenges, as well as policies and strategies that respond to local prospects and concerns regarding development.

At the same time, indicators and criteria based on the perspective of communities can help define priorities and the notion of development that are compatible with local livelihoods. For example, in the analyzed case, indicators related to the role of women in the economic activities of the communities (participation in fishing and in assemblies) show attention to gender inequality; and the emphasis on information related to lake surveillance indicates concern about security and illegal activity in the region. Positive outcomes related to the empowerment and autonomy of communities, economic stability and security to carry out their activities may be more important than increases in income alone. Indeed, studies that take into account socio-cultural aspects such as culture reproduction, social capital and empowerment find more positive outcomes in NTFP trade than analyzes focused only on material gains (mainly income) (De Mello et al., 2020).

Finally, the proposed methods and indicators have some limitations. The need of adapting indicators to capture relevant specificities of each chain may compromise the comparability of bioeconomy's cases, and a more rigorous assessment of each case may depend on long-term follow-up. The present assessment of the pirarucu bioeconomy provided a broad picture of the present strengths and challenges of the productive chain, however could't it convey sufficient information about the past trajectory of communities. In order to evaluate and monitor the evolution of this bioeconomy, the study needs to be replicated over time. Communities should evaluate these results and indicate possible gaps and new criteria to be included. We also believe the method should be applied to more cases to certify its viability, and specially its ability to generate reliable comparisons and evidence to guide public policies.

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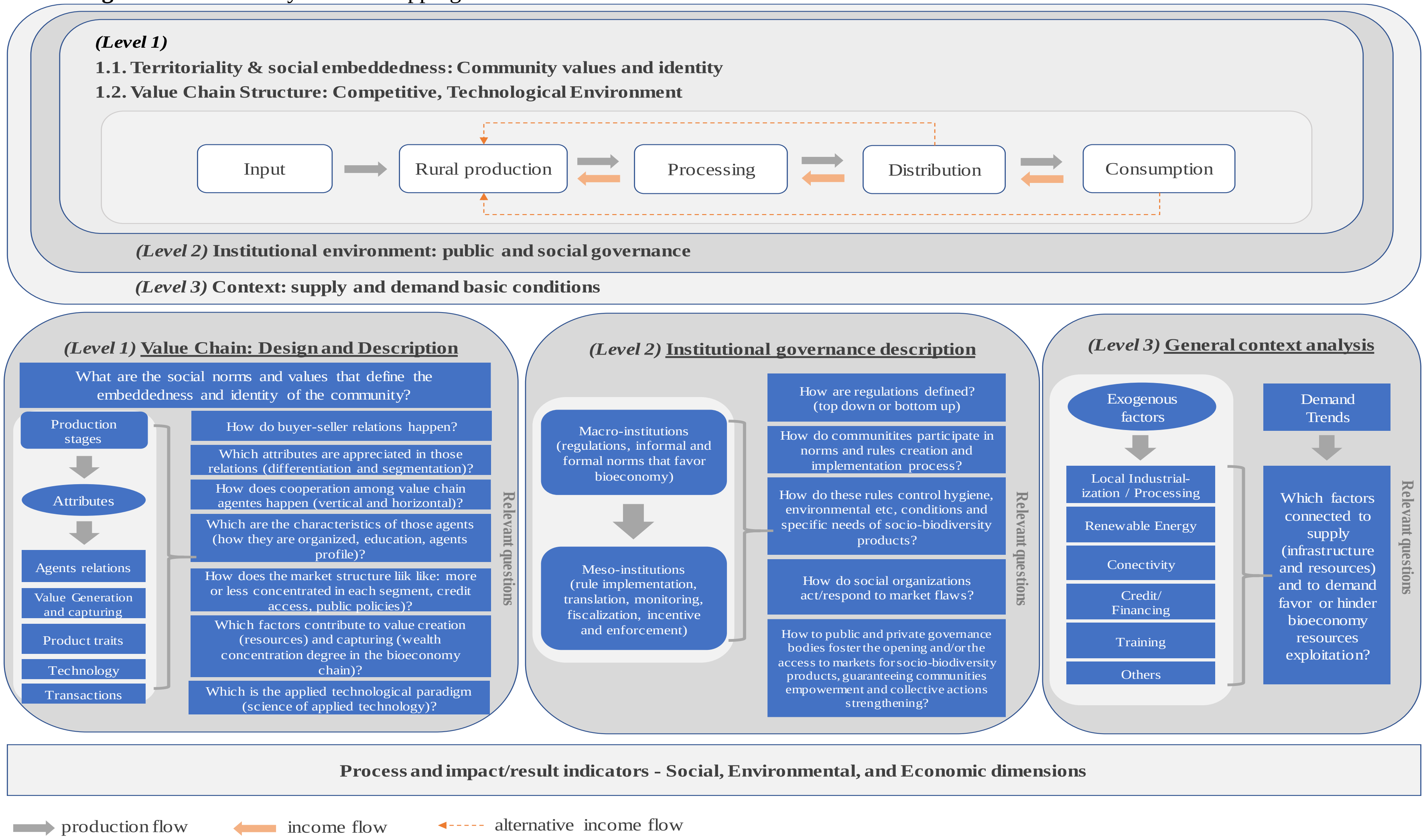
Figure 1: Bioeconomy Chains Mapping Model



Source: Farina and Zylbersztajn (1998); Saes and Silveira (2014); Neves et al. (2020); Neven (2014), North, 1990, Ostrom et al , 2010; Ménard & Shirley, 2018, Becker, 1990.

Table 1. Bioeconomy targets and potential criteria of evaluation

Bioeconomy targets	*Scale of analysis*	*Type of Information*	*References*
Social: Strengthening cultural diversity. Integration of S&T knowledge to local community knowledge, aiming at human well-being			
Potential evaluation criteria			
Education and training of human resources	**C / T**	**SD/ PD**	Rossi, 2013; Barrientos et al., 2011; UNSDN, 2012; Gereffi et al., 2005; Reinecke and Posthuma, 2019; Humphrey and Schmitz, 2004; Mani et al., 2018; Ostrom et al., 2012; Ostrom, 2010; Laven ,2009.
Health quality	**T**	**SD**	
Social governance: communities' participation in decision-making process (*top down/bottom up*). Youth and women participation	**C / VC**	**PD / N**	
Collective action, and Respect for local culture and knowledge, Decision making rule, Community attributes	**C/VC**	**N**	
Environmental: Goods and services production process that safeguards biomes' resilience and biodiversity conservation			
Potential evaluation criteria			
Biodiversity conservation (Forest area, Lake protection)	**T**	**SD**	Azevedo-Ramos et al., 2020; Achabou et al., 2017; Peralta et al, 2018.
Water / Soil management	**T**	**SD**	
Waste recovery (Circular economy)	**T**	**SD**	
Economic: Improved income generation/ well-being: transparent and equitable market access			
Potential evaluation criteria			
Income generation and distribution	**C/VC**	**PD/N**	Petesque, 2020; Golini et al., 2018; Jindra et al., 2019; Ostrom et al., 2012.
Market access and commercialization	**C/VC**	**PD/N**	

Note: (T) Territorial; (VC) Value Chain; (SD) Secondary Data; (N) narratives, (PD) Primary Data
Source: The authors.

Table 2. Process and Impact/Result Indicators

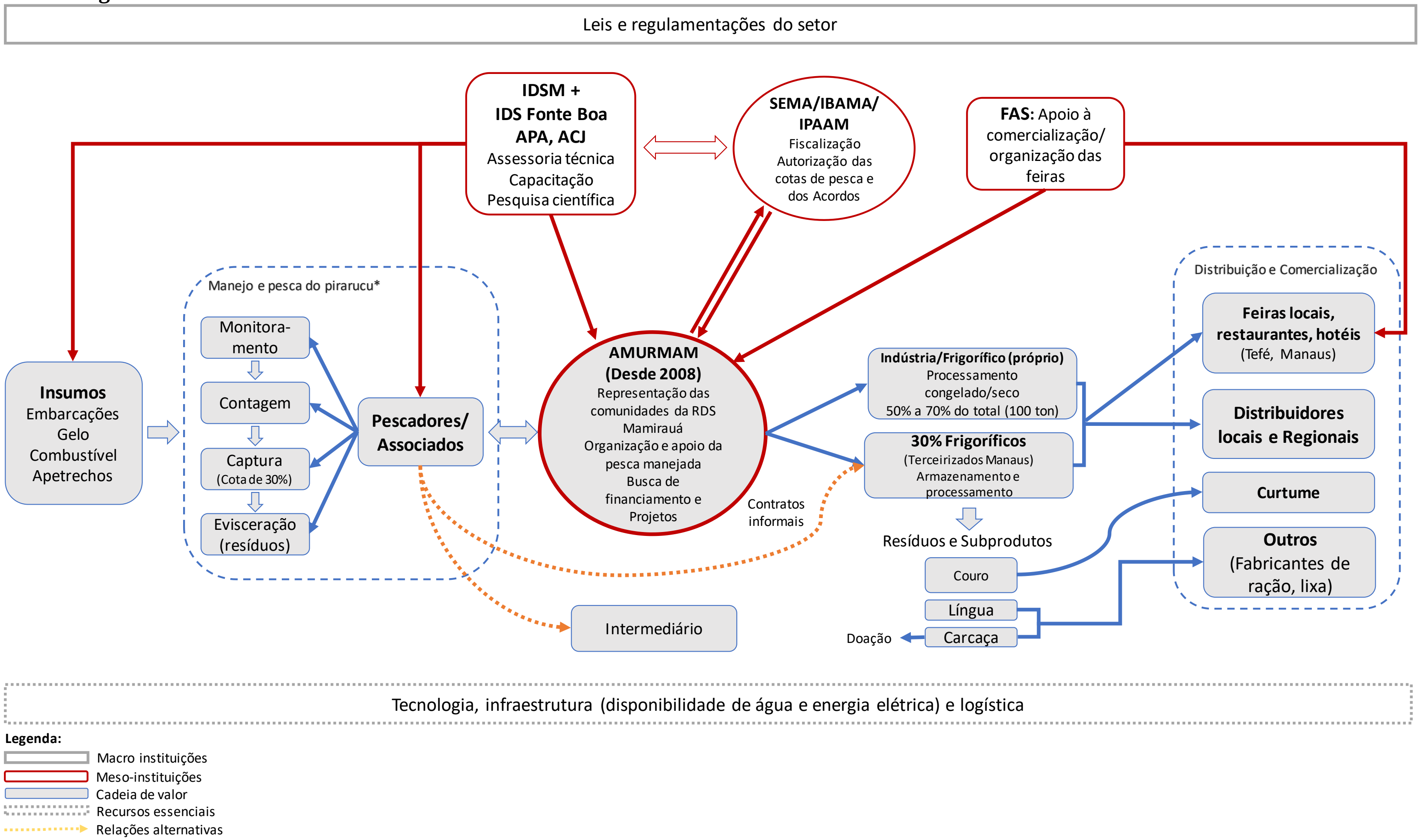
Potential evaluation criteria		Metrics/Indicators	Tiers	Outputs/Outcomes	Source
Bioeconomy targets: Social dimension Strengthening cultural diversity. Integration of S&T knowledge to local community knowledge, aiming at human well-being.					
Potential evaluation criteria		**Metrics/Indicators**	**Tiers**	**Outputs/Outcomes**	**Source**
Education and training of human resources	1	HDI education	T	Education: average of the Maraã, Fonte Boa and Urani municipalities*: 2005 - 0.308 and 2016 - 0.498 (rate of growth: 61.69%)	Firjan[1]
	2	% of fishermen trained in the year in relation to the total	T	25.94% of fishermen in 2021 (between men and women) (Trained = 248 people; Total = 956 fishermen)	IDSM Report[2]
Health	3	HDI health	T	Health: average of the Maraã, Fonte Boa and Urani municipalities*: 2005 - 0.398 and 2016 - 0.621 (rate of growth: 56.03%)	Firjan[1]
Social governance: communities' participation in decision-making process (top down/bottom up). Youth and women participation.	4	% of women's participation in fishing activities	C	Average participation rate of women in fishing = 38.2% in 2021.	IDSM Report[2]
	5	Participation of women in assemblies	C	It was reported during the conversation circle that women began to have a large participation in assemblies and in the definition of income distribution rules.	Field research[3]
Collective action, and Respect for local culture and knowledge, Decision making rule, Community attributes	6	Rate of change in the number of communities participating in fishing	T	number of communities involved in fishing: 1999 = 4 communities, 2017 = 42 communities. Rate of change: 950% (52.78% for year)	IDSM Report[2]
	7	Generations involved in fishing in the community	C	83.9% of respondents mentioned having started fishing because of family influence, grandparents and parents were fishermen.	Field research[3]
	8	Support from social organizations: qualitative, type of organization (local, international, university, church)	VC	Were identified as main [4]: • Amurnam: local, role: coordination of fishermen. • FAS: local coverage, chain coordination and training. • Idsm: Regional coverage, training and development. • Sebrae: National coverage, training and entrepreneurship initiatives.	Field research[3]
Bioeconomy targets: Environmental dimension Goods and services production process that safeguards biomes' resilience and biodiversity conservation					
Potential evaluation criteria		**Metrics/Indicators**	**Scale**	**Outputs/Outcomes**	**Source**

Biodiversity conservation (Forest area, Lake protection)	9	Vegetation cover evolution rate	T	Vegetation coverage: average of the areas Maraã, Fonte Boa and Urani*: 2000 - 1,165,197 he; 2020 - 1,153,268 he; growth rate: -1,02 (Amazônia Bioma growth rate was - 5.81 for the same period)	MapBiomas[5]
	10	Pirarucu population growth rate (average per community)	T	Increase in pirarucu population in lakes: 533% , 29,62% for year (1999 = 627 un; 2017 = 3,970 un)	IDSM Report[2]
Water / Soil management	11	Rate of evolution of the water surface	T	Water surface: average of the areas Maraã, Fonte Boa and Urani*: 2000 - 87,263 he and 2020 - 92,166 he; growth rate: +5.62.	MapBiomas[5]
Bioeconomy targets: Economic dimension Improved income generation/ well-being: transparent and equitable market access.					
Potential evaluation criteria	**Metrics/Indicators**		**Scale**	**Outputs/Outcomes**	**Source**
Income generation and distribution	12	Employment and income	T	Employment and income: average of the Maraã, Fonte Boa and Urani municipalities*: 2005 - 0.272 and 2016 - 0.247	Firjan[1]
	13	number of fishermen benefited per yea	T	Number of communities involved in fishing: 1999 = 42 fishermen and 2017 = 1,590 (growth rate: + 3.685% ~ average 204.76% for year)	IDSM Report[2]
	14	Other sources of income	VC	Fishermen receive closed season insurance (*defeso*) or *Bolsa Floresta* or *Bolsa Família* (government programs).	Field research[2]
	15	Gross average income per fisherman	VC	Average gross earnings per fisher: 1999 - R$ 402.46; 2011 - R$ 1,574.26 and 2017 - R$ 1,739.38.	IDSM Report[2]
Market access and commercialization	16	Participation in fairs	C	58.1% of respondents sell at fairs. Participation in fairs promoted by FAS in Manaus was reported. FAS mobilizes fishermen to negotiate their production, promoting the practice of better prices.	Field research[3]
	17	number of buyers	C	58.1% of respondents reported having only 1 buyer.	Field research[3]
	18	Market share of commercialization	VC	86.4% state regional market (Manaus, Manacapuru and Parintins) 9.6% interstate market (Santarém/PA, Itapoã and Oeste/RO) 4.0% local regional market (Tefé, Alvarães and Maraã).	IDSM Report[2]
	19	Participation in institutional programs		No cases were reported where commercialization was carried out for institutional/governmental programs.	Field research[3]
	20	How it is traded (whole/processed / salted / leather)	C	The community does not process the pirarucu, they just remove the viscera and sell it, which means that the fish is sold with less added value. Field research data: 87.1% of fishermen sell whole ("charuto")	Field research[3] IDSM Report[2]

				Data from the IDSM report: 97.7% were traded as gutted whole fish and only 2.3% as fresh manta.	
	21	Distribution of income along the chain	VC	Communities 15%; Intermediaries 35%; slaughterhouses 50%.	Bartkus et. al (2002)
Certification	22	Types of certification/collective trademark	VC	Denominação de Origem Mamirauá para o pirarucu manejado de nove municípios do Amazonas (Alvarães, Fonte Boa, Japurá, Juruá, Jutaí, Maraã, Tefé, Tonantins e Uarini).	INPI[5]
Production costs	23	Estimated critical production cost	VC	Cost of monitoring the lakes represents about 50% of the total cost	Field research[3]
Infrastructure	24	Access to drinking water	C	67.74% have access to piped water.	Field research[3]
	25	Access to electricity	C	90.3% have access to electricity. They use a diesel generator (light engine, in some cases available only from 6 pm to 10 pm)	Field research[3]
	26	Access to the internet	C	22.58% of respondents have poor quality internet access.	Field research[3]
	27	Access to basic sanitation	C	Absence of basic sanitation in the visited community	Field research (observation)
	28	Access to the media	C	93.5% of respondents use cell phones	Field research[3]

Notes:
[1] The Firjan index ranges from 0 (minimum) to 1 point (maximum) to classify the level of each location into four categories: low (from 0 to 0.4), regular (0.4 to 0.6), moderate (from 0 .6 to 0.8) and high (0.8 to 1) development. Source: https://www.firjan.com.br/ifdm/
https://www.mamiraua.org.br/documentos/4163f5aaff5d05e1a9e1804bb5e06307.pdf
[2] Annual Technical Report 2021 (IDSM, 2022).
[3] Questionnaires applied to 31 fishermen and women during field research.
[4] Amurmam (Associação dos Moradores e Usuários da RDSM Antonio Martins); FAS (Fundação Amazonas Sustentável); Idsm (Instituto de Desenvolvimento Sustentável Mamirauá); Sebrae (Serviço Brasileiro de Apoio às Micro e Pequenas Empresas).
[5] https://mapbiomas.org/
[6] https://www.gov.br/inpi/pt-br/central-de-conteudo/noticias/inpi-reconhece-a-denominacao-de-origem-mamiraua-para-o-pirarucu-manejado
* These municipalities were chosen because their main source of economic activity is pirarucu.
Source: The authors.

Figure 2. SDR Mamirauá Pirarucu Value Chain



Source: Project FAPESP Nº 2020/08886-1.