

Theoretical-empirical Articles

Experimentalist Governance in Bioeconomy: Insights from the Brazilian Amazon

Governança Experimentalista em Bioeconomia: Insights da Amazônia Brasileira



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ABSTRACT

Objective: understand whether subnational processes to develop bioeconomy policy are integrated with local implementation efforts in the state of Amazonas. **Theoretical framework:** experimentalist governance. **Methods:** deductive content analysis was conducted in three phases: open and axial coding and integration of theory. **Results:** a nascent system of experimentalist governance to foment bioeconomy is taking shape. However, the potential for experimentalism to improve policy reforms is far from realized due to policy coordination problems, incipient collective action among actors, and the absence of incentives to promote experimentation and systematic learning from local experiences. The quintuple helix innovation model is a promising approach to engage different actors in the design and implementation of bioeconomy experiments, where the state actor assumes central coordination and local actors implement. Political will and long-term strategy based on metrics and a system for review are essential. **Conclusion:** the experimentalist problem-solving approach could have a significant impact in the Amazonian bioeconomy by demonstrating and replicating the successful initiatives to generate useful local policy experiments, learning, and promoting socioeconomic opportunities with environmental conservation. Policy experimentation can be a new viable alternative to move state and non-state actors from conflict based on divergent economic interests to a cooperative means to promote socioeconomic development by demonstrating and escalating success cases that can foster policies and opportunities.

Keywords: Amazon; bioeconomy; biodiversity-based economy; experimentalist governance; environmental governance.

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RESUMO

Objetivo: entender se os processos subnacionais nas políticas em bioeconomia são integrados aos esforços de implementação local no estado do Amazonas. **Marco Teórico:** governança experimentalista. **Métodos:** análise de conteúdo dedutiva em três níveis: codificação aberta e axial e integração da teoria. **Resultados:** um incipiente sistema de governança experimentalista foi identificado no fomento da bioeconomia amazônica. No entanto, o potencial da governança experimentalista no aprimoramento da política apresenta problemas de coordenação na implementação, ação coletiva entre os atores e ausência de incentivos para promover experimentação e aprendizado sistemático das experiências locais. O modelo de inovação da hélice quintupla é uma abordagem promissora que envolve diferentes atores no design e implementação de experimentos em bioeconomia, onde o governo assume a coordenação central e os atores locais implementam as iniciativas. Vontade política e estratégia de longo prazo com base em métricas e um sistema de revisão por pares são essenciais. **Conclusão:** a abordagem experimentalista de resolução de problemas pode ter um impacto significativo na bioeconomia ao demonstrar e replicar as iniciativas bem-sucedidas na política pública no nível local, aprendizado sistêmico e promoção de oportunidades socioeconômicas com conservação ambiental. A experimentação em políticas pode ser uma nova alternativa viável para mover atores de conflitos baseados em interesses econômicos divergentes para um sistema colaborativo que promova o desenvolvimento socioeconômico e oportunidades na região.

Palavras-chave: Amazônia; bioeconomia; economia baseada na biodiversidade; governança experimentalista; governança ambiental.

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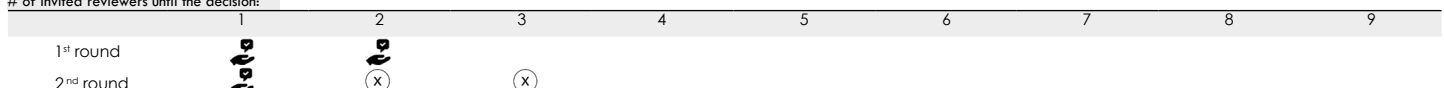
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INTRODUCTION

Tropical forests play major roles in global climate change through the carbon stocks in mitigation and climate regulation. Such environment services depend on reversing forest loss, increasing sustainable management practices with local benefits and practices (Gould et al., 2024).

The Legal Amazon is an area of more than five million km² (60% of Brazil) comprising the states of Acre, Amapá, Amazonas, Maranhão, Mato Grosso, Pará, Rondônia, Roraima, and Tocantins. About 29 million people live in the territory with the lowest socioeconomic indicators in the country (Instituto Brasileiro de Geografia e Estatística [IBGE], 2024).

The Brazilian Amazon has lost at least 17% of its forest cover. Illegal logging, expansion of agricultural areas, and wildfire outbreaks are the leading causes of deforestation (Instituto Nacional de Pesquisas Espaciais [INPE], 2024).

Collective responses to large-scale challenges such as climate change and deforestation require local empowerment to set goals based on diversity of local priorities (McDermott et al., 2022). Decentralized governance can facilitate the participation of non-state actors and the distribution of power that shapes the implementation arrangements (Viana et al., 2016). That is the case of Amazonian bioeconomy, which is increasingly important in academia due to its policy relevance as a socioeconomic development to reduce emissions from deforestation and forest degradation.

Although the Amazon is far from the scientific and technological frontier of the contemporary bioeconomy, its high biodiversity presents significant economic opportunities for the region while benefiting local communities and preserving the standing forest (Abramovay et al., 2021). The establishment of a bioeconomy public policy at subnational level requires governance arrangements, goals and metrics, financial resources, and a definition of responsibilities of the state and non-state actors for implementation at the local level (Marcovitch & Pinsky, 2020).

Bioeconomy emerges as a solution to curb deforestation and forest degradation, while creating socioeconomic value and contribute to the sustainable development in biomes such as the Amazon, one of the most biodiverse places on earth (Abramovay et al., 2021; Guedes et al., 2012).

It is considered a promising approach that combines socio-economic development with a strong environmental protection perspective (Vivien et al., 2019).

It seeks sustainable ways of producing and consuming resources (Gawel et al., 2019), while respecting planetary boundaries (Rockström et al., 2023).

A governance system and implementation arrangements in bioeconomy are critical to ensure sustainable development while resolving trade-offs. Public policies in bioeconomy should be built on three pillars: territorial management within ecological boundaries, sustainable value chains, and social fairness and fair transition, considering the impact on the most vulnerable people. Indeed, the bioeconomy policy architecture should rely on sectoral policies across policy areas, with vertical coordination between different levels (European Commission, 2022; OECD, 2009).

Despite the significance of social and economic issues for a bioeconomy transition, studies from a social science perspective are largely lacking (Sanz-Hernández et al., 2019). There are gaps in policy and research that warrant further attention in bioeconomy, such as self-reflexivity in identifying policy problems and solutions (Ramcilovic-Suominen et al., 2022). Still, there is a gap of systematic research focused on the socio-biodiversity aspects of bioeconomy in the Amazon (Saes et al., 2023).

This paper focuses on the Amazonian bioeconomy context, which considers forest conservation and socio-ecological benefits as guiding principles (Bergamo et al., 2022). Understanding how different policies and measures may address high complexity problems (e.g., deforestation and poverty) in a jurisdiction with a wide variety of actors and interventions is important for rule making (Gebara et al., 2019).

This study aims to understand whether (and how) subnational processes to develop bioeconomy policy are integrated with local implementation efforts in the Brazilian state of Amazonas. By using the experimentalist governance theory (Sabel & Zeitlin, 2008) to understand if the experimental problem-solving approach is supporting the design (or not) of the emergent public policy governing system, this paper advance knowledge about bioeconomy policy implementation, which is at the forefront of academic debates and that are of practical significance and policy relevance in climate change, ecological economics, and circular bioeconomy.

The empirical results are of practical significance and policy relevance as it examines how different forms of policy and governance emerge from local actors, and how this may be influential in a high diversity environmental context at regional and global scales. Indeed, the federal government instituted in June 2024 the Bioeconomy National Strategy (Presidential Decree no. 12,044/2024) (Brasil, 2024) with the strategic

guidelines to the National Bioeconomy Development Plan.

For practitioners and academics who study the architecture of public policies, this Brazilian sectorial case is particularly interesting, as success through fostering the bioeconomy in the state of the Amazon contributes to reduction of deforestation and forest degradation, preservation of biodiversity, guaranteeing of environmental services, and promotion of sustainable development of local communities.

LITERATURE REVIEW

The literature review is organized on two fronts. First, concept of bioeconomy is contextualized for the Amazon. Second, experimentalist governance is presented as the theoretical framework for this study.

Bioeconomy

The concept of bioeconomy gained prominence in the early 2000s with the adoption of an agenda focused on biotechnology by the European Union (European Commission, 2018) and the Organization for Economic Cooperation and Development (OECD, 2009). The initial approach aimed at a biomass-based economy to transition from fossil fuel in the production of energy and materials to biological-based inputs from agriculture (Langeveld et al., 2010; Vivien et al., 2019). The current concept of bioeconomy is far more encompassing.

Bioeconomy is still a controversial term and is used with several different meanings. Authors from the Global South — especially in high biodiverse regions — focus the discussion on social, cultural, and local biodiversity issues (Saes et al., 2023). Others define bioeconomy centered on economic and technological development aspects considering the environment externalities (Bergamo et al., 2022). A global bioeconomy would be regenerative and balance managing natural global commons (Ostrom, 2000), while improving human well-being with technological, organizational, and social innovations (El-Chichakli et al., 2016).

Bioeconomy is more than an economic sector, as it involves a set of ethical-normative values rather than descriptive definition on relationships between different sectors by adding greater value to the products of extractivism and greater equity in the distribution of this value between actors in the socio-biodiversity value chains (Abramovay et al., 2021). Social equality and fair benefit sharing are important outcomes for bioeconomy governance instead of normative goals of a public policy that aims to promote structural changes (Lima, 2021).

There seems to be little consensus on the definition of bioeconomy and what bioeconomy implies in the Amazon context (Costa et al., 2022). The Brazilian Presidential Decree no. 12,044/2024 institutes the National Bioeconomy Strategy and defines bioeconomy as:

Model of productive and economic development based on values of justice, ethics and inclusion, capable of generating products, processes and services, efficiently, based on the sustainable use, regeneration and conservation of biodiversity, guided by scientific and traditional knowledge and its innovations and technologies, with a view to adding value, generating job and income, sustainability and climate balance (Brasil, 2024).

The Brazilian State of Amazonas Secretariat for Economic Development, Science, Technology, and Innovation (SEDECTI) relates the bioeconomy concept to economic activities based on the production, commercialization, and distribution of environmental assets from the Amazon, including forest production (timber and non-timber), pharmaceuticals, fine chemicals, fishing, and fruit growing. By definition, bioeconomy is classified in three types: socio-biodiversity, forest-based, and commodities. However, the bioeconomy policy approach proposed by the state of Amazon, which is the unity of analysis of this research, considers only economic activities based on the socio-biodiversity value chains. Other forms of agricultural production are subject of different policies as large-scale production (e.g., monoculture) requires different policy approaches.

According to the definition of SEDECTI for the state, the socio-biodiversity bioeconomy is based on extractivism and traditional family agriculture. It is highly dependent on biodiversity resources and ecosystem services but has low environmental impact. In the forest-based bioeconomy, use of resources takes place with the intensive management of specific species, with large-scale production. The commodity-based bioeconomy comprises agribusiness, plantation forestry, and biotechnology, demanding high levels of investment, productive knowledge network, intensive use of technology for industrial and business purposes, and may include family producers downstream in the supply chain (Schor et al., 2021).

As per the public policy statement at the subnational level, the Amazonian bioeconomy is based on economic and commercial activities that involve sustainable socio-biodiversity value chains, including fruits, nuts, and fish. It aims to strengthen local economies, sustaining an approach that aims at standing forests, flowing rivers, and

a strong community component. It is based on ethical and normative standards to transform the relationship between society and nature, supported by science, technology, and innovation. Indeed, strengthening traditional knowledge and promoting well-being and income generation for forest peoples are fundamental pillars of a regenerative people-centered public policy based on the use of material and energy resources, while promoting socioeconomic development (Abramovay et al., 2021).

With this conceptual lens, Amazonian bioeconomy transcends the mainstream forest-based products approach and the replacement of biodiversity with monocultures (Fearnside, 2017) by assuring zero deforestation, diversification of methods and production valuing biodiversity as a response to widespread monoculture plantations, and equitable benefit sharing for local communities (Bergamo et al., 2022).

Experimentalist governance theory

The research's conceptual model is based on the experimentalist governance theory (Sabel & Zeitlin, 2008). This theory was designed to study the policymaking process based on conditions of complexity and uncertainty to regulators and organizations that require working on ground-level problem solving to create and connect novel responses. That is the case of the Amazonian bioeconomy, as a socioeconomic approach to promote the sustainable development of the territories focused on conservation, inclusion, and human well-being.

The concept was proposed by Sabel and Zeitlin (2008) as a theoretical framework to guide research on the formulation process of public policy through collective action between regional institutions and member states in various sectors in the EU. The purpose was to understand how different levels of government solve highly complex governance problems under uncertainty by engaging different stakeholders through a recursive learning process sustained by setting targets and reviews of ground-level initiatives by regulators, private sector, academia, and civil society actors (Eckert & Börzel, 2012; Zeitlin, 2016).

Experimentalism is an organizational structure based on self-monitoring through a learning-by-doing process between ground-level problem solvers and top-down regulators. Deliberations based on doubt and disagreement between actors are used to progress on policy implementation despite uncertainty, combined with a set of incentives to encourage innovation (Sabel & Victor, 2022).

The experimentalist governance framework is based on four elements: (1) a set of goals and broad metrics; (2) implementation by lower-level actors with incentives to explore solutions and innovate; (3) regular checks, monitoring, and peer review of results; and (4) review of goals, metrics, and procedures considering implementation experience (Sabel & Zeitlin, 2008). Different institutional and implementation arrangements are required to operationalize these four pillars, which is a non-linear recursive process (De Burca et al., 2013).

The experimentalist architecture demands higher levels for rule-making and lower-level actors with autonomy to implement their own solutions according to local circumstances, and report results for a central coordination (Sabel & Zeitlin, 2008).

Peer reviews serve as a mechanism for helping key actors to learn systematically from local implementation. They involve consultation and accountability without a traditional bureaucratic rule-making process (De Burca et al., 2013). Indeed, deliberation and organization in the experimentalist approach are neither a top-down nor a bottom-up approach. Results from local implementation influence the rule making process, as the absence of a clear hierarchy and bureaucracy gives space to innovation and collective learning (Sabel & Zeitlin, 2008).

In this system, peer review of local experiments is essential to support decision making in policy, as lower-level actors are responsible for putting policies into practice through the implementation of initiatives. Joint learning between actors at different levels leads to improvements, revision of goals and rules in highly complex context based on uncertainty, where solutions are expected to be co-designed (Sabel & Victor, 2022).

METHODS

Research design — Theoretical framework

The study's conceptual model was designed through the lens of the experimentalist governance theory, based on the theoretical framework as adapted by Pinsky et al. (2020), which is adequate for this research because it was designed and empirically tested to guide research on the public policy formulation process involving complex problems through collective action between state and non-state actors. The framework is formed of seven analytic categories: strategy, financing, multilevel institutions, implementation, stakeholder participation, collective action, and collective learning (see Figure 1). The nascent bioeconomy in the Brazilian state of Amazonas was analyzed as a sectoral case study (Yin, 2004).

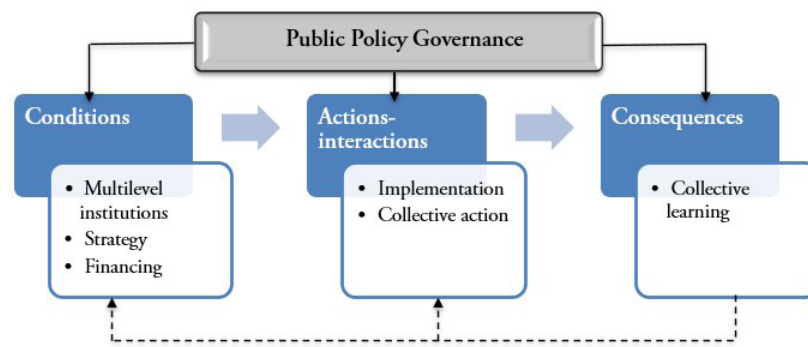


Figure 1. Experimentalist governance system theoretical framework.

Source: Based on Pinsky, V., Kruglianskas, I., & Gomes, C. M. (2020). Conducting research in climate finance in Latin America: Challenges and opportunities of using grounded theory methodology approach. *Global Journal of Flexible Systems Management*, 1–12. <https://doi.org/10.1007/s40171-020-00241-x>

The conceptual framework represents a non-linear and continuous management process based on conditions and consequences, resulting from actions-interactions between actors and groups at different levels. Applied to the Amazonian bioeconomy case, the lack of a national bioeconomy policy highlights the circumstances in the Brazilian state of Amazonas that influence the dynamics of the emergent governance system based on uncertainty and actions-interactions of state and non-state actors.

Strategy, financing, and multi-level institutions are the conditions for the implementation of the policy via a governance, which require the establishment of a strategy for policymaking and implementation at local level. Financing is a necessary condition for policy implementation. The process requires actions and interactions by and between actors and groups through stakeholder participation to enable collective action during policy formulation and implementation. Collective learning is the expected output of the feedback system in the experimentalist governance process.

The theoretical framework proposed by Pinsky et al. (2020) was conceived by using the grounded theory (Corbin & Strauss, 2015), which is a powerful method to comprehend processes and experiments based on the logical relation to a problem that require collective actions. This research tested the conceptual framework, that is intended to propose solutions to real-world problems based in a pragmatic and meaningful way. The methodological decision was to use the framework to guide primary data collection and discuss the results through the lens of the experimentalist governance theory. Each of the seven categories are discussed empirically, and not theoretically, in the section Results.

Sampling

A research protocol to select sampling was developed. First, a core sample was determined, and referrals were included based on the snowball method (Biernacki & Waldorf, 1981) to form of non-random sampling where generalization, representativeness, and external validity were not sought after (Parker et al., 2019). To minimize the limitations and bias of the technique, participant inclusion criteria were determined by the importance of the institution they represent, practical knowledge and involvement with Amazonian bioeconomy in implementation or in policymaking. The list of research participants was also validated with public policy agents from SEDECTI to guarantee a high-level and diverse sample, including agents from civil society, private and public sector that are involved in the emerging bioeconomy public policy. Data variation was considered by selecting participants with different expertise, economic interests, and positions. In total, 19 interviews were conducted.

Data collection and analysis

A semi-structured interview guide with open-ended questions was constructed based on the seven analytic categories proposed by Pinsky et al. (2020). Interview transcripts were the core information of the study, with 17 hours of content that were recorded and transcribed.

Deductive content analysis was conducted using the three-level coding technique — open, axial, and theoretical integration (Corbin & Strauss, 2015; Sampieri et al., 2006). Through the lens of the experimentalist governance theory (Sabel & Zeitlin, 2008), the emergent multilevel governance in Amazonian bioeconomy

was analyzed. The analysis considers the management structure and institutional arrangements at the state level, rulemaking, policy implementation, monitoring and assessment, and system for review to understand how learning and adjustment occur.

Deductive content analysis was conducted in three major phases. First, interview transcripts were treated and analyzed through an open coding process. Information was categorized according to similarities found in the data. Quotations (important segments of data) were created manually, based on interview transcripts, and then linked to a code that resulted in a set of 23 codes — seven pre-determined codes (Table 1), as per the theoretical framework, and 16 new codes that emerged inductively from data analysis. With the support of Atlas.ti, 219 quotations were codified.

Table 1. First phase coding process.

#	Code	Frequency
1	Strategy	48
2	Experimentalism	41
3	Implementation	40
4	Collective action	34
5	Collective learning	23
6	Multilevel institutions	15
7	Bioeconomy actor	14
8	Distinct interests	14
9	Finance	9
10	Incentive	9
11	Chain constraint	8
12	Capacity	6
13	Benefit sharing	6
14	Bioeconomy concept	4
15	Intermediary role	4
16	Associativism cooperativism	3
17	Circular bioeconomy	3
18	Stakeholder participation	2
19	Manager profile	2
20	Product traceability	2
21	Technological transfer	2
22	Business model	1
23	One-size-fits-all	1

Note. Elaborated by the authors.

The second phase was axial coding, where codes were consolidated according to their groundedness (coding frequency) and recurrence, resulting in a reduced number of codes with similar meaning (concepts). The third phase involved further consolidation of these concepts into higher-level categories by validating the experimentalist governance theoretical framework for the case study. In the following sessions, major empirical results are presented and discussed through the theoretical framework.

RESULTS

This study did not intend to analyze projects or initiatives at the local level. The objective was to understand whether (and how) subnational processes to develop bioeconomy policy are integrated with local implementation efforts in the Brazilian state of Amazonas focused on a multilevel governance approach.

The experimentalist governance conceptual framework was used as theoretical lens, formed by seven analytic categories: multilevel institutions, strategy, financing, implementation, stakeholder participation, collective action and learning (Pinsky et al., 2020). During data analysis, the category ‘stakeholder participation’ was incorporated into ‘multilevel institutions’ since this study did not intend to understand in depth how different state and non-state actors interact with each other in the Amazonian bioeconomy. The following data analysis is organized by the resulting six analytic categories.

Multilevel institutions

An incipient bioeconomy policy was found in the state of Amazonas. Due to the absence of laws and regulations at the federal level by the time data was collected, a nascent bioeconomy system formed by state and non-state actors is emerging at subnational level. Coalitions and networks of different actors with common objectives are formed, aiming to influence the policymaking process and discuss sustainable business models focused on the challenges and opportunities within the socio-biodiversity value chains (e.g., Brazil nut).

Multilevel institutions are implementing local initiatives considering the value of environmental assets, traditional knowledge, income generation, and community well-being. However, the absence of formal multilevel governance is leading to policy coordination problems due

to the lack of collective action between actors in the territory.

We found major actors involved in nascent public policy on bioeconomy, including federal and subnational governments, civil society organizations, international cooperation agencies, academia, and the private sector.

Some of these actors work collaboratively in initiatives. However, there are weak links between participation and collective actions from multilevel institutions that encourage experimentation on the ground. InovaSocioBio Amazonas was the only program that involves different actors at local level of implementation with a central coordination at subnational government. This pilot project intended to strengthen three socio-biodiversity value chains by testing a policy intervention and measuring its effectiveness. This program is based on the quintuple helix innovation model that emphasizes the natural environment for knowledge production and innovation in bioeconomy (Carayannis & Campbell, 2011), while involving public and private sectors, academia, civil society, and development institutions in the implementation process.

Strategy

By the time primary data was collected, federal government did not have a national bioeconomy public policy. Brazil lunched in June 2024 a decret with guidelines to establish a National Bioeconomy Strategy. Fragmented initiatives were found at national level within the Ministry of Agriculture (MAPA). The state of Amazonas has a nascent bioeconomy policy agenda with initiatives distributed across different secretariats. The nascent rule making process, the lack of a governance system based on goals and metrics, and constant changes in public leadership are critical constraints to the establishment of a bioeconomy policy.

Political and technical alignment between government bodies at different levels is crucial to set a transversal bioeconomy policy. Even though SEDECTI was leading the policy agenda in the state of Amazonas, the State Secretariat for the Environment and the State Secretariat for Rural Production had a different understanding of priority programs, and divergent positions and economic interests. The absence of a central coordination was a major constraint on policy design and implementation strategy. The bioeconomy strategy was a government and political initiative instead of a state agenda that aimed to foster long-term regional socioeconomic development and environmental protection.

SEDECTI was responsible for designing and implementing a structured bioeconomy program. First, the technical team developed a conceptual framework applied to the context of the state, which was intended to be the foundational bioeconomy strategy, with centralized coordination and local implementation.

Amazonian bioeconomy was defined in the state strategic plan as “a set of economic activities for production, commercialization, distribution and consumption of goods and services derived from Amazon socio-biodiversity resources in a sustainable and innovative way” (Schor et al., 2021 p. 1). Circular bioeconomy, priority economic activities based on natural resources, financial instruments, participatory governance structure and the key role of the cooperatives and associations were some of the structuring pillars for policy design.

The ‘Knowledge Production Network’ was the policy approach proposed by SEDECTI, instead of working individually with the socio-biodiversity value chains such as Brazil nut. In the Brazilian state of Amazonas, networks are fundamental to understanding the socio-biodiversity market structures and design collaborative mechanisms to develop an inclusive bioeconomy. It refers to an integrated system formed by interdependent actors and processes involving education, research, management, production, processing, distribution, commercialization, and consumption of socio-biodiversity products and services that relies on cultural identity, traditional knowledge, and fair benefit sharing (Schor et al., 2021).

A two-year public consultation was conducted and resulted in a technical paper that contributed to the revision of the Brazilian state of Amazonas Environmental Economic Law (4,419/2016 (Lei nº 4.419, 2016). The intention was to include policy guidelines in the Bioeconomy Structuring Program and ongoing initiatives in the state legislation.

The request to update the law was submitted to the Presidency Chief of Staff (Casa Civil) by December 2021. Updating a state law should have been faster than starting a rulemaking process to propose a new bioeconomy law for the Amazonian Bioeconomy State Strategy. The reelected government, however, withdrew the request and suspended most of the ongoing bioeconomy initiatives coordinated by the state. The technical team responsible for policy implementation was dismissed.

Some major constraints were found in policymaking and strategy design, such as the lack of socioeconomic indicators. The Brazilian state of Amazonas does not

have statistical data nor information on territorial organization and demographics (socioeconomic indicators) at the local level. Establishing a public policy strategy demands metrics to measure results and impacts, based on a framework goal and a system to support the policymaking process.

The government does not have demographic data even to prepare the four-year Brazilian state of Amazonas pluriannual planning. Public policy initiatives are implemented but results are not measured. In the context of bioeconomy, the state government does not know the market-size or the annual production of socio-biodiversity value chains; they only have estimates. This makes it even harder to identify the constraints to develop the sector.

According to federal legislation, every municipality with more than 20,000 inhabitants must prepare pluriannual planning and have it approved in the chamber to avoid sanctions. Empirical evidence shows that most policymakers at the municipal level have neither the institutional nor technical capacity to prepare a strategic plan for territorial and environmental development, neither do they have it to design and implement structuring initiatives to foment transversal public policy. This context has direct implications for the development of inclusive bioeconomy, which depends on territorial development, access to health and education, and the strengthening of associations, cooperatives, and indigenous people's organizations.

Research participants indicated important issues that should be considered as foundational elements in a bioeconomy strategy and rule-making process, including capacity building initiatives focused on policymakers and public managers at the local level and insertion of the bioeconomy strategy in the municipal pluriannual plan for budgeting.

Guaranteeing a fair benefit sharing, working conditions, and provision of basic services (health, education, security) among extractivist communities for human well-being is a major challenge in bioeconomy policymaking. Additionally, sanitary protocols and product traceability, including human rights, child labor, working conditions, and deforestation-free, are prerequisites for doing business, specially exporting.

We also found that technical qualification, professional trajectory, and purpose of the policymakers responsible for rulemaking and strategy design are determining factors to leading transversal policy implementation and addressing complex problems by involving several actors with different interests.

Financing

The lack of incentives and financing resources for strengthening cooperatives and associations was a major

constraint to developing the Amazonian bioeconomy, especially in the interior of the state. Pupunha and guarana are examples of biodiversity products that could stimulate local development and income generation through extractivist activities if there were appropriate incentives and financial resources.

Bioeconomy public policy should encourage the economic development of socio-biodiversity value chains according to the territory's vocation, considering local culture. Bioeconomy activities demand infrastructure and investment in processing areas in the interior of the state.

Another constraint in bioeconomy financing is related to the small scale of experiments and different risk/return ratios for investors. Commercial and traditional banks do not usually assume high risk credit operations, which demand venture capital as a major financing source. Research participants inform that financing to scale bioeconomy initiatives is a major challenge because investors are insecure on the legal and financial risks involved in an ecosystem based on uncertainty and experimentation.

Different mechanisms were found in the emerging Amazonian bioeconomy financing ecosystem. [Fundação CERTI \(2022\)](#) classified them in four pillars: (1) regular mechanisms for public funding (e.g., Brazilian Development Bank, Brazilian state of Amazonas Funding Agency, Amazon Development Superintendent); (2) special funding programs (e.g., Amazon Fund, GIZ's Bioeconomy and Value Chains Program); (3) philanthropic investment and funding (e.g., Arapyau Institute, Vale Fund, JBS Fund); and (4) impact investment mechanisms (Idesam, Conexsus, Sitawi).

Bioeconomy experiments involving blended finance structures, venture capital and non-refundable investment are increasing. Despite this, high risk investment is necessary for seed capital, incubation, and acceleration of impact businesses to implement innovative solutions and test new business models. State policy and incentives in bioeconomy are needed to engage more private investors.

This study did not seek to analyze the effectiveness of the existing financial mechanisms. However, the lack of collective action and integrated programs aimed at reducing risk, qualifying innovative initiatives to develop and test new business models, was pointed by participants as a significant barrier to the development of a robust and flexible financing ecosystem to induce innovation through local experimentation.

Experimentation in new finance models is important to improve traditional funding mechanisms.

Implementation

The one-size-fits-all approach does not apply in the Amazonian bioeconomy. Social and territorial development and implementation of local initiatives that reflect the communities' desire and vocation are fundamental conditions for an inclusive bioeconomy approach.

Scale in the Amazon bioeconomy occurs at the local level in micro-regions through a set of experiments that are designed according to the specificities in the territory and local culture. Replication of experiments at scale is rarely a feasible approach due to the dispersion of extractivist communities. This requires local implementation with central coordination at regional level.

Bioeconomy strategy and experimental design focusing on developing socio-biodiversity value chains should consider the dynamics of product collection in the forest, commercial barriers, and the key role of local communities to maintain the standing forest while protecting the integrity of environmental services. Scaling in the Amazon bioeconomy may require the expansion of production areas that could threaten forested areas.

The extractivist community's livelihood depends on a set of economic activities in the territory that generate income and well-being. Research participants point that the development of local productive arrangements, considering the vocation of the territory, local culture, traditional knowledge, and the agricultural calendar (collecting periods) should be structuring pillars in the design of any bioeconomy initiative that combines different extractivist activities. Territories are bioeconomy ecosystems with diverse productive activities that generate subsistence, employment, income, and well-being for communities. There are different periods of production and that may demand great effort over a few months for collection, considering the challenges related to the forest environment.

Capacity building for producers and extractivist communities is another challenge. Technology, science, innovation, and technical assistance are the foundations of the development of socio-biodiversity value chains, which demands training and technology transfer to small rural producers, as they account for more than 95% of the production in the Amazon. Indeed, capacity building for associations and cooperatives managers is key, especially for community-based and extractivist

organizations. Basic training programs on financial planning and control are necessary to strengthen organizations and commercialization.

Different business models to commercialize socio-biodiversity products have been used in the region for decades, including enterprises focused on the international market (e.g., CIEX) and others in the national premium market for certified products with traceability (e.g., Fazenda Aruanã) in the Brazil nut market. Each business demands a set of incentives and policy mechanisms. Technology to improve productivity is welcome, as long as it does not generate exploitation based on the limits of the artisanal production and scales.

Fair benefit sharing is a complex issue in bioeconomy, as the extractivist communities are the weakest link in the socio-biodiversity value chain. Most of them operate through intermediary agents, who determine the product's price, facilitate the commercialization, and guarantee the purchase in the season. Intermediaries are often essential in isolated communities or when there is not minimal social organization.

The federal government has a Minimum Price Guarantee Policy (PGPM), established by National Supply Company (CONAB), that applies to socio-biodiversity products. It is an important tool to reduce income fluctuations from rural producers and ensure a minimum price. However, the regulated price is too low and does not ensure fair distribution of benefits among local producers. The intermediaries easily cover this minimum price that CONAB prescribes.

Valuing the cost of labor in agroextractivist communities is complex to measure, and difficult to consider in PGPM and intermediaries' pricing. The development of strategies on how to value the community's workforce should be reconsidered in the implementation of experiments.

A long-term state public policy instead of a four-year-government-program is essential to consolidate the experiments and enable investments above historical levels in bioeconomy. Structuring processes through local productive arrangements, territorial and landscape development approach instead of looking for the value chains individually is recommended.

InovaSocioBio Amazonas Program

This pilot project was designed and implemented by SEDECTI as part of the nascent bioeconomy public policy at the subnational level. The program's

goal was to strengthen three socio-biodiversity chains (Brazil nuts, wild pirarucu, and guarana), as part of the Amazonas Bioeconomy Structuring Program (PPA 2020-2023 — Amazon Government). The program was financed by MAPA, and designed on three pillars: (1) diagnosis, development, and strengthening of socio-biodiversity production chains; (2) development of an Amazon commodity exchange; and (3) strengthening the bioeconomy system formed by actors at subnational level. The initiative intended to benefit 7,543 agroextractivists in 21 municipalities, including micro entrepreneurs, associations and cooperatives, extension technicians and financial agents.

Through an experimentalist governance approach, the initiative aimed to reduce information asymmetry in socio-biodiversity value chains, promote technological innovation, structure a certification and traceability process for socio-biodiversity products, increase access to rural credit, and develop innovation workshops and networking.

The quintuple helix innovation model was considered in the strategy and design by involving different stakeholders and multilevel institutions during implementation — a combination of bottom-up (local level institutions for implementation) and top-down (central policy coordination) approaches was used to reduce bureaucracy, induce innovation, experimentation, and identify the structuring foundations for the policymaking process.

Even though the Brazilian state of Amazonas is yet to implement a bioeconomy strategy, the InovaSocioBio tested a collaborative approach through multistakeholder governance by involving academia, civil society, and the private sector. However, this initiative was discontinued in 2022 due to political and personnel changes within the reelected state government. Since that governance dismantlement, bioeconomy policy has not been a priority program for the state, which refocused policy efforts to support agribusiness (commodities) and mining sectors in the Brazilian state of Amazonas.

German cooperation (GIZ), which financed part of the program, suspended its support due to the lack of institutional dialogue with the new public leaders. Bidding and purchasing processes were suspended, making it impossible to deploy the program's budget, and remaining funds were returned to MAPA before the end of the fiscal year.

Even though the initiative involved international cooperation agencies, the private sector, and academia, institutionalization of experiments did not occur in projects that had financial resources managed by

the state government due to political conflicts and administrative inefficiency in application of the budget. A key challenge in institutionalizing bioeconomy policy initiatives is centralized coordination of governance, while implementation must be carried out by local actors with autonomy. Centralized implementation from the state actor is bureaucratic and uncertain due to divergent interests in the political agenda, especially in election years.

On the other hand, state participants point out that the quintuple helix innovation model and multilevel governance are effective approaches to minimize problems if the project's financial resources have already been transferred to the organization responsible for implementation at the local level. Articulation and central coordination at the subnational level are key roles for policymakers, considering the design of experiments and monitoring of results and impacts.

Collective action

Policymaking in bioeconomy is complex and requires collective action from different actors to design transversal public policies, strategies, and find solutions for systemic problems such as poverty and deforestation. Consensus among actors on bioeconomy has not yet been reached. Arriving at a conceptual definition of bioeconomy is a complex task, even among state actors, due to divergent interests of small economic groups such as the monoculture of socio-biodiversity products (e.g., açai fruit).

We find a weak bioeconomy governance and rulemaking process that relies on collective action to design experiments and test pilot projects at the local level. Civil society organizations have the expertise to implement initiatives in the territories as they are engaged with extractivists and forest peoples, know the challenges in the territory, and have the technical knowledge to work with community leaders. NGOs compete for financial resources and projects. In the absence of central coordination and state articulation in the territory, these organizations do not often speak to each other, except when there are financial resources involved. In some cases, there are overlapping resources in the same community and/or initiative.

Strengthening socio-biodiversity value chains while promoting ecological conservation and socio-economic development requires high levels of integration, articulation, and collective action between different actors in capacity building, logistics, financial resources, and marketing channels. The absence of the state in mediating conflicts and supporting community-based organizations, cooperatives, and associations may weaken productive activity.

A successful example of collective action through networking is the ‘Coletivo da Castanha,’ financially supported by UNDP. Different actors (agroextractivists, agroindustries, buyers, academia, and government) in the Brazil nut value chain have been working collectively to discuss critical themes such as price fluctuation, problems with intermediaries, and commercialization.

Structured dialogue and collective learning between different actors in bioeconomy is crucial. Despite this, no systematic process was found. An important experiment in the Western Amazon region was found in implementation — the Bioeconomy Priority Program (PPBio). The program was designed by the Manaus Free Trade Zone Superintendent (Suframa) and has been implemented by the non-profit IDESAM, aiming to raise funds for mandatory investments in R&D (Informatics Law) to generate new products, services, and businesses for the Amazon bioeconomy. PPBio works as a connecting agent between research institutes, universities, companies, startups, and the government.

Uma Concertação pela Amazônia and the Amazon Bioeconomy Hub are also examples of collective action initiatives that intend to discuss important issues, generate knowledge, influence public policy, and catalyze multisectoral solutions to build a more inclusive Amazon bioeconomy. However, these coalitions are regarded by some as discussion forums with incipient effective collaboration to promote transformational changes in the region.

Empirical evidence indicates the absence of collective action even among state actors due to conflicting interests in the bioeconomy policy agenda. At the municipal level, the dynamic between a few families who take turns in power is very complex. This will require full involvement and articulation from the state government to articulate bioeconomy policies.

The lack of a bioeconomy strategy and policy guidelines at the subnational level to mediate the political power game and conflicts between small interest groups at the local level was found as a major constraint to collective action. On the other hand, the quintuple helix innovation model is a promising approach for engaging different state and non-state actors in bioeconomy experiments through integrated actions in the territories.

Collective learning

Collective learning was identified by research participants as a type of learning developed from actions-interactions between actors and groups in

response to specific situations in which joint actions were needed, such as problem solving and strengthening the positions of coalitions and alliances, which is related to technology transfer and recursive learning processes.

Technology transfer in the Amazonian bioeconomy and academic experiments conducted by universities and research institutions (e.g., EMBRAPA and INPA) need improvement. Participants reveal that important scientific knowledge is generated in the region but is not transferred as social technology to either local communities or producers. One of the reasons for this is the lack of continuity of research projects and effective mechanisms for technology transfer to strengthen socio-biodiversity value chains.

Indeed, the lack of policy incentives to articulate the bases of scientific and technological knowledge, basic and applied science, was identified as a major bottleneck to move the research agenda to the next level of implementation, diffusion, and adoption of innovations to strengthen socio-biodiversity value chains in the region.

Some participants identified the need for entrepreneurs and financiers to be willing to take risks and acquire knowledge to fund more experiments at local level. Understanding what does and does not work in practice to identify promising initiatives for scale and impact should be an imperative to foster the Amazonian bioeconomy.

Embrapa Amazonas has successful experience with a research project called Social Innovation, which involves associations and cooperatives finding technological solutions to social problems. Through the maturity scale approach of technological assets, research is operationalized based on solving practical problems (productive sector and value chains), working collaboratively with technical assistance bodies to transfer applied knowledge to society and the productive sector.

Identifying the most appropriate communication formats to ensure that information reaches the productive sector is of paramount importance, considering that internet connection is precarious or non-existent in some territories. Academics and practitioners pointed that the research agenda in the region must be connected to real world problems to foment the bioeconomy according to social and economic needs. Private funding for scientific research could be more relevant with more collective action between universities and the productive sector to encourage knowledge transfer.

No systematic knowledge sharing platform was found at the state level, neither was one found between

non-state actors implementing bioeconomy initiatives in the same territory. There is not a systematic collective learning process on what does and doesn't work in practice to support replication of successful experiments implemented by local actors. Neither is there any among coalitions or civil society movements such as *Uma Concertação pela Amazônia*. Measuring results of experiments through a peer review process would support rulemaking in prioritizing programs.

The systematization of results from local experimentation should be strategic for state governments to evaluate the experiments that are being implemented in the territory, with the objective to analyze successful initiatives that could be replicate in other micro regions. According to research participants, there are different solutions and social technologies spread across the Amazon that do not connect with each other. Indeed, there are resistances and difficulties in connecting state and non-state actors to design and implement effective actions collaboratively in the bioeconomy ecosystem. This requires a paradigm shift from competition to collaboration, once actors realize that exponential problems are escalating in the region, and the linear approach no longer works — collaboration, cooperation, and multilevel governance are needed.

DISCUSSION

The experimentalist governance approach has been praised for its ability to promote innovation, responsiveness, and legitimacy in policymaking. It encourages the use of pilot projects and other forms of experimentation to test different policy interventions and gather data on their effectiveness. Through ongoing peer review and learning, experimentalist governance seeks to develop public policies that are responsive to challenging circumstances, where solutions for highly complex problems are unavailable and demand the involvement of diverse stakeholders and collective actions in different levels (De Burca et al., 2013; Eckert & Börzel, 2012; Sabel & Victor, 2015; 2022; Sabel & Zeitlin, 2008).

This research could not find the experimentalist governance policy approach practically implemented in the context of bioeconomy in the state of the Amazon. The principles of experimentalist governance were not identified at the macro-level processes of the Amazonian bioeconomy nor integrated with local efforts at implementation.

The four elements of the experimentalist approach in the policymaking process were not found, including: (1) setting broad framework goals and metrics; (2)

discretion granted during implementation to lower-level units that have incentives to explore options; (3) regular reporting, monitoring, and peer review of results; and (4) revision of goals, metrics, and procedures in light of the implementation experience (Sabel & Zeitlin, 2008).

The development of the Amazonian bioeconomy is complex, uncertain, and relies on a challenging policy context due to divergent ideological and economic interests among state and non-state actors. The traditional hierarchical governance approach for rulemaking and revision based on implementation experiences results (Mathieu & Rangoni, 2019) was not found. Initiatives were implemented by different actors without a peer review process and revision of metrics at the subnational level in light of what worked or not at the local level.

Current policy processes and initiatives conducted by different actors seem to be insufficient to develop the socio-biodiversity value chains in the Brazilian state of Amazonas. The definition of priority topics in rulemaking demands the construction of transversal policies and institutional arrangements (Abramovay et al., 2021), including collective action, risk-taking financing, collective learning, and knowledge transfer to replicate successful experiments in different territories. Transparency, stakeholder participation, and accountability are important in the rulemaking.

An incipient bioeconomy policy design intended to induce experimentation and innovation in a pilot program in the Brazilian state of Amazonas was found. Most of the bioeconomy experiments have been implemented by civil society actors without central coordination at state level. A recursive experimentation and learning process, based on whether initiatives work on the ground (Pinsky et al., 2019), was not found at the subnational level.

Instead, weak governance in the nascent Amazon bioeconomy due to policy coordination problems was found. There is no clear definition of roles and responsibilities in bioeconomy policy at the subnational and local levels. Incipient implementation arrangements and a fragile rule-making process point the lack of priority to foster bioeconomy as a promising policy approach to develop the region. There is no multilevel governance process (Ostrom & Janssen, 2005), nor systematic actions to include civil society and the private sector as major contributors in the policymaking process (Sabel & Zeitlin, 2008).

The institutionalization of any long-term project should happen at the local level with the involvement of civil society, and the municipality

leading implementation, with central coordination and a system for review at the state level to integrate policies and institutionalize successful initiatives.

Instead, some bioeconomy experiments lacked an integrated approach from the policy standpoint, and had weak institutional articulation capacity at the local level. No clear commitment to adopting an inclusive bioeconomy policy approach nor priority criteria were identified at the subnational level. The Brazilian state of Amazonas has policies that support bioeconomy from different perspectives (e.g., family agriculture, regional development, science, and technology) but without central coordination.

Collective learning appears in different ways in bioeconomy in the Brazilian state of Amazonas but lacks a subnational strategy that promotes a more inclusive view of the relationship and major roles of different state actors, considering the systematization of knowledge produced in academic research and local experiments. Framework goals and peer review processes are fundamental elements in the experimentalist governance approach (Sabel & Victor, 2022). We could not find a recursive learning process based on the revision of goals, procedures, and/or practices considering the results and lessons learned from implementation due to policy coordination problems (Eckert & Börzel, 2012). Promoting science, technology, and innovation through a systematic knowledge sharing platform was identified as an opportunity to advance Amazonian bioeconomy.

The private sector has not seen investment opportunities at scale to access new markets in the Amazon bioeconomy. The role of the state in promoting the bioeconomy through subsidies, technical assistance, and supporting the conversion of knowledge and experiments into business is essential. All research participants agreed that state government should add value and strengthen socio-biodiversity value chains by focusing on articulation, design of experiments, and facilitation processes. Implementation should always take place at local level by civil society organizations, academic and research institutions, or the private sector. The promising InovaSocioBio program was only discontinued by the state government due to conflicting interests in the transition of secretaries that decided to prioritize interests of economic groups in mining and agrobusiness and not in bioeconomy.

Several key lessons can be drawn from these findings. 'First', the development of inclusive bioeconomy requires a policy design approach that considers the diversity and territorial adversities at the local level to define the strategy, governance structure, policy instruments, and implementation arrangements

to attract financial flows to fund experiments. Territorial and landscape development are the structuring basis to foster the Amazonian bioeconomy, as well as innovative approaches in the production. Weak policy coordination and incipient collective actions among different state and non-state actors can aggravate territorial problems due to the lack of a system to review to support policy and decision making.

An emerging Amazonian bioeconomy was identified, but it is not systemically connected within the scope of the public policy at subnational level, neither is it connected to the innovation ecosystem to finance forest-based enterprises and startups. Information is very diffuse due to the lack of a knowledge sharing platform. Institutions are implementing local initiatives, but the absence of multilevel governance system and central coordination may be leading to the lack of collective action among actors in the same territory.

'Second', the institutionalization of the Amazonian bioeconomy as a state policy did not take place in the case study due to policy coordination problems and divergent economic interests between state actors. The absence of central coordination at state level is a major constraint to policy design and implementation strategy. Amazon bioeconomy was perceived as a government and political initiative instead of state agenda that aims at regional socioeconomic development with environmental protection in the long term.

Even though bioeconomy is a promising approach to provide opportunities for combating poverty and inequality through the sustainable use of forest biodiversity (Abramovay et al., 2021), collective action problems were found even among small groups because each actor ignores costs imposed on others (Hardin, 1982). The vulnerability and fragility of the institutions are subject to political interests. For example, the circular bioeconomy approach was inexistent in state policy, even though it could generate income opportunities, such as the use of organic waste to produce by-products (Rocha et al., 2022).

On the other hand, the quintuple helix innovation model in the InovaSocioBio program was found to be an effective approach to co-create solutions to develop the bioeconomy and strength the socio-biodiversity value chains that are not ready in the Amazonian bioeconomy, considering the involvement of diverse actors with different competencies. The combination of bottom-up and top-down approaches in policymaking may be effective in the case study, aiming to reduce bureaucracy, induce innovation through experimentation, and identify the structuring foundations for the rulemaking process.

State actors should assume the central coordination and provide the funds for local actors implement experiments. Political will and long-term strategy based on metrics and a system for review are essential. Delegate the implementation for local level actors should minimize the risks of political intervention based on the interests of powerful economic groups. Collective learning was not reached in the InovaSocioBio since the program did not have a system for review in light of the implementation experience.

‘Third’, the development of an inclusive biodiversity-driven economy in the Amazon (Nobre & Nobre, 2018) demands an experimentalist approach to strengthening socio-biodiversity value chains, while promoting sustainable development in the region, focused on human well-being.

The absence of collective action may lead to policy coordination problems due to the lack of systematic learning from challenges and opportunities in bioeconomy based on what works (or not) in practice. Stakeholder participation and collective action are needed in an experimentalist governance that relies on collaborative and adaptive processes to engage a wide range of actors with different policy approaches to learn from and improve over time (Pinsky et al., 2019).

An incipient structure to build knowledge systematically due to weak links in policy articulation between actors was identified. Innovative bioeconomy initiatives that aim to improve social inclusion and income generation based on the quintuple helix innovation model (Carayannis & Campbell, 2011) could lead to transformational changes. These changes will take place if different actors are involved and committed to experimentation during the implementation process and systematization of lessons learned from the ground.

Indeed, bottlenecks in the major socio-biodiversity value chains in the Amazon are well-known in the literature (e.g., Abramovay et al., 2021; Bergamo et al., 2022; Ferreira et al., 2020). Overcoming obstacles demands an experimentalist approach during local implementation, collective action with central coordination to take advantage of bioeconomy opportunities in the domestic and international markets. Adding value to raw biodiversity products, improving the quality of products and promoting the sustainable use of forests while promoting income generation and well-being should be the structuring pillars to regional development. An inclusive Amazonian bioeconomy requires an effective involvement of local communities in policymaking, which were not identified. Valuing traditional knowledge and recognizing the important role of traditional and indigenous peoples, whose knowledge incorporates the history of complex cultural

systems and domestication of the regional biodiversity, should be non-negotiable foundations for an inclusive Amazonian bioeconomy.

CONCLUSIONS

Bioeconomy is a promising socioeconomic approach to promote the transformative changes needed to address poverty and inequality while protecting the environment. Unlocking the potential of the Amazon bioeconomy demands different conceptions of policymaking, economic instruments, and implementation arrangements to support an inclusive socioeconomic development model that promotes the sustainable use of nature — a governance system based on local partnership and experimentation. In this paper, we use the theory of experimentalist governance to understand whether (and how) the emerging bioeconomy public policy in the Brazilian state of Amazonas is integrated with local efforts at implementation.

Although Brazil lunched in June 2024 a decret with guidelines to establish a National Bioeconomy Strategy, the National Bioeconomy Development Plan has not been defined so far. The implementation plan must contain actions, goals, financial resources, metrics and indicators, normative, regulatory, and fiscal instruments for policy implementation at different levels. This study suggests that the experimentalist governance could overcome some of the challenges in the rule-making and policy-implementation processes to ensure that the national policy translates into concrete practices and outcomes at the local level.

The governance process of implementing a bioeconomy policy should be based on an experimentalist process through a learning-by-doing approach. Lessons learned from this process may improve rulemaking, considering successful experiences. It requires a participatory governance structure in the policy architecture that should rely on sectoral policies across policy areas, with vertical coordination at different levels to manage divergent positions and interests of actors and avoid political power games to implement a state agenda instead of four-year government effort.

Policy coordination in the Amazonian bioeconomy at different levels should be a priority for reducing deforestation, while promoting sustainable development in the region. The articulation of a transversal bioeconomy policy at the national level with central coordination at state level local implementation is strategic to foster the development of a circular, regenerative, low-carbon, and inclusive economy centered on human well-being and conservation of ecosystems.

Weak links were identified between the bioeconomy public policy governing system in the Brazilian state of Amazonas with local efforts at implementation. At the local level, capacity building initiatives focused on policymakers and public managers are necessary to design a strategy and include it in the municipal pluriannual plan for budgeting.

Defining priority activities in the Amazonian bioeconomy and establishing a strategic plan with

goals, metrics, governance, accountability, effective implementation arrangements, and financing resources are the structuring base for policymaking at state level. Indeed, a new paradigm needs to be built based on the circular bioeconomy approach, based on sustainable ways of producing and consuming socio-biodiversity products. Opportunities could be extended to new business models, technology-based start-ups, logistics, certification, monitoring, and traceability systems.

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1st author: conceptualization (lead), data curation (lead), formal analysis (lead), funding acquisition (supporting), investigation (lead), methodology (lead), project administration (lead), resources (lead), validation (lead), visualization (lead), writing - original draft (lead), writing - review & editing (lead).

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