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Socio-ecological metabolism and climate justice: insights from the Brazilian Semi-Arid Region[1]

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Abstract

The convergence of climate change, environmental degradation, and persistent rural inequalities has intensified concerns about the sustainability of agri-food systems, particularly in vulnerable dryland regions. In the Brazilian Semi-Arid, agroecology has emerged as a promising alternative to the productivist agricultural model; however, important questions remain regarding its scalability, evaluation, governance, and contributions to climate justice. This article critically examines the extent to which agroecological peasant agriculture can foster resilient and equitable development. Drawing on a socio-ecological metabolism framework, the study systematizes evidence from family farming experiences, territorial networks, and collective action initiatives through six analytical axes: socio-ecological impacts, scales and limits, transformative metrics, gender and youth, participatory governance, and climate justice. It proposes the METRA model (Metabolism of Energy, Work, and Matter), which operationalizes socio-ecological metabolism into indicators applicable to public policy monitoring and the Sustainable Development Goals. The findings suggest that, under appropriate institutional conditions, agroecology strengthens socio-ecological resilience, enhances peasant autonomy, promotes inclusive governance, and provides a viable pathway toward sustainable development and climate justice in the Semi-Arid and beyond.

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1. Introduction

Contemporary agri-food systems face interconnected environmental, social, and economic challenges that threaten their long-term sustainability. Climate change, biodiversity loss, land degradation, and water scarcity increasingly interact with persistent rural poverty, food insecurity, and social inequality, particularly in vulnerable regions of the Global South (IPCC, 2023; UNCCD, 2017). These challenges are widely recognized as consequences of dominant development models characterized by intensive resource extraction, dependence on external inputs, and the progressive degradation of ecological and social systems (Martínez-Alier, 2008; Foster, 2011).

The Brazilian Semi-Arid region provides a particularly relevant context for examining these dynamics. Covering approximately 1.4 million km² and home to around 31 million inhabitants, including nearly 10 million rural residents, the region combines recurrent droughts, fragile ecosystems, and increasing risks of desertification with one of the largest concentrations of family farming in Latin America (IBGE, 2017; Pérez-Marín et al., 2022). Historically, agricultural modernization policies promoted input-intensive production systems that frequently overlooked local ecological and socioeconomic conditions, contributing to environmental degradation, agrobiodiversity loss, rural indebtedness, and migration (Altieri, 1995; Silva et al., 2020).

In response to these challenges, agroecology has emerged as a scientific, practical, and socio-political alternative grounded in the principle of coexistence with the Semi-Arid region (ASA, 2011; Altieri, 2002; Wezel et al., 2009). Through networks of farmers, civil society organizations, and public institutions, agroecological initiatives have fostered diversified farming systems, community seed banks, agroecological markets, participatory certification schemes, and innovative governance arrangements. Empirical evidence points to positive outcomes in food self-provisioning, productive diversification, ecological restoration, drought resilience, and the empowerment of women and youth (Petersen et al., 2017; Barbosa & Gallar Hernández, 2025; Borges Pequeno et al., 2025).

Despite these advances, significant analytical and policy challenges remain. Conventional agricultural assessment frameworks continue to prioritize productivity and monetary outputs while overlooking critical dimensions such as autonomy, resilience, ecological regeneration, and social inclusion. Furthermore, important questions persist regarding the scalability of agroecological systems, their long-term effects on gender relations and rural youth, their governance implications, and their potential contributions to climate justice and sustainable development.

This article addresses these challenges by examining the contributions, limitations, and future prospects of agroecological transitions in the Brazilian Semi-Arid. Specifically, it asks to what extent agroecological peasant farming contributes to sustainable rural

development, socio-ecological resilience, and climate justice, and how such contributions can be systematically assessed. The analysis is informed by the socio-ecological metabolism approach, which examines the flows of energy, matter, and labor linking society and nature and provides an integrated framework for evaluating agroecosystem performance beyond conventional productivity indicators (González de Molina & Toledo, 2023).

Drawing on accumulated evidence from agroecological experiences across the region, the article examines six interrelated dimensions: impacts and outcomes; scales and limits of expansion; metrics and indicators; gender, power, and youth; governance and participatory democracy; and agroecology and climate justice. The findings indicate that agroecological systems strengthen ecological regeneration, food security, productive resilience, and social inclusion while enhancing local capacities for climate adaptation and mitigation. As a conceptual contribution, the article proposes the METRA model (Metabolism of Energy, Work and Matter) as a framework for operationalizing socio-ecological metabolism in the assessment of public policies and progress toward the Sustainable Development Goals, and illustrates its application using ecological-economic data from agroecosystems in the region.

The remainder of the paper is organized as follows. Section 2 reviews the theoretical foundations of socio-ecological metabolism and agroecology. Section 3 presents the analytical framework and methodological approach. Section 4 examines agroecological experiences in the Brazilian Semi-Arid. Section 5 discusses the main findings and contributions of the study. Finally, Section 6 concludes.

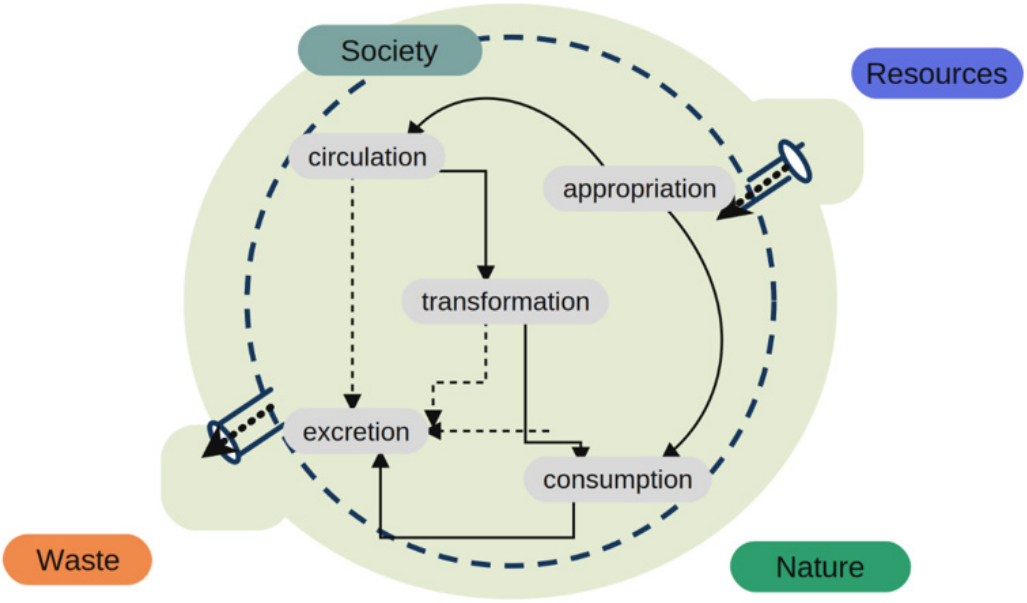
2. Theoretical framework

2.1 Socioecological metabolism: an analytical key

The concept of socio-ecological metabolism (Figure 1), also called the social metabolism of nature, has its roots in political ecology and ecological economics (Martínez-Alier, 2008; Foster, 2011). It refers to the set of flows of energy, matter, and labor that articulate natural and social processes, allowing us to understand how human societies appropriate, transform, and return resources to nature (González de Molina & Toledo, 2023; Martínez-Alier, 2008). This concept allows peasant practices—such as nutrient recycling or the integration of activities—to be translated into analytical categories that dialogue with international literature (Borges Pequeno et al., 2025; Petersen et al., 2017; Pérez-Marín et al., 2017a).

In modern agricultural systems, these flows tend to be linear, based on intensive extraction, reliance on external inputs, and large-scale waste disposal. This linearity produces negative externalities – erosion, loss of fertility, water pollution and loss of biodiversity – that weaken the ecological reproduction capacity of territories (Altieri, 1995; Rosenzweig & Hillel, 2008; Petersen et al., 2017). In the Brazilian Semi-Arid region, the uncritical adoption of this model, imported from other contexts,

Figure 1. Diagram of socio-ecological metabolism: flows between nature and society



Note: Socio-ecological metabolism describes how society appropriates resources from nature, transforms and consumes them, in turn generating internal circulation and the excretion of waste that returns to the natural environment. This diagram makes it possible to visualize the interdependence between social and ecological processes, as well as the impacts that the linear model of resource use can produce in terms of degradation and loss of resilience. By contrast, agroecology seeks to reorganize these flows toward more circular and sustainable circuits, promoting recycling, regeneration, and waste reduction.

Source: Petersen et al., 2017; Borges Pequeno et al., 2025.

generated more harm than solutions, increasing the vulnerability of rural families to droughts and market crises.

In contrast, agroecologically based peasant agroecosystems tend to organize circular flows, promoting nutrient cycles, biomass recycling, and integration of complementary activities (Gliessman, 1990; Toledo, 1990; Altieri, 2002). These systems internalize a large part of the energy and material needed, reduce monetary costs and increase autonomy in the face of the market. In the Semi-Arid region, the practice of reincorporating biomass, diversifying crops, or integrating animals into production not only stabilized productivity, but also strengthened community trust and family sovereignty.

By applying socio-ecological metabolism as an analytical key for the Brazilian Semi-Arid Region, critical questions are opened: what combinations of energy, matter, and labor flows maximize the resilience of agroecosystems to climate and market shocks? What indicators can translate these interactions into metrics applicable to public policies and sustainable development strategies? (Astier et al., 2008; González de Molina & Toledo, 2023; Petersen

et al., 2017). This perspective makes it possible to articulate peasant knowledge—based on the observation of climate, soil, and biodiversity—with global analytical frameworks, creating a bridge between science, policy, and local practices.

2.2. Agroecology in the Brazilian Semi-Arid

The Brazilian Semi-Arid region encompasses a range of internationally recognized agroecological experiences that have emerged as strategies for living with semi-aridity and addressing its socio-environmental challenges (ASA, 2011; Duque, 2008; Pérez-Marín et al., 2017a; Petersen et al., 2017; Barbosa & Gallar Hernández, 2025). These experiences include social water technologies, such as rainwater harvesting cisterns, barreiros (small reservoirs), and stone tanks; community seed banks; home and productive gardens; agroforestry systems; and participatory certification schemes. Although often simple in design, these initiatives have significantly improved living conditions, reduced social and environmental vulnerabilities, and fostered pathways toward more sustainable and resilient livelihoods (Gliessman, 2007).

These initiatives also embody the principles summarized by FAO (2018) in its ten elements of agroecology: diversity, synergies, efficiency, recycling, resilience, co-creation and sharing of knowledge, human and social values, food culture and traditions, responsible governance, and circular and solidarity economies. Far from being abstract concepts, these elements are manifested in the everyday practices of rural families through the diversification of production systems, the conservation and exchange of native seeds, the strengthening of women's networks, and the establishment of collective arrangements for water governance and resource management.

A central challenge, however, lies in translating these principles into concrete practices, public policies, and evaluative frameworks. In the Brazilian Semi-Arid, networks such as the Articulação Semiárido Brasileiro (ASA), the Polo da Borborema, and the Araripe Ecoregion Network (ECOARARIPE), together with organizations including the Centro Sabiá, the Assessoria e Serviços a Projetos em Agricultura Alternativa (AS-PTA), the Center for Labor Studies and Social Action (CETRA), the Instituto Regional da Pequena Agropecuária Apropriada (IRPAA), and the Programa de Aplicação de Tecnologias Apropriadas às Comunidades (PATAC), have functioned as "living laboratories" of agroecological innovation. Through their actions, these actors have developed territorial arrangements that integrate ecological management, social innovation, and political advocacy.

The experience accumulated by these organizations demonstrates that agroecological transitions are not driven solely by the adoption of technical practices. Rather, they depend on the capacity to articulate scientific knowledge, local and traditional expertise, collective action, and supportive public policies within a shared vision of socio-ecological transformation.

2.3. Governance and Participatory Democracy

Recent literature highlights that the sustainability of agroecological systems depends not only on productive practices but also on inclusive and democratic governance arrangements (De la Cruz & Dessein, 2021). In the Brazilian Semi-Arid Region, the ways in which communities organize themselves, make collective decisions, and manage common resources are as critical to resilience as the agricultural techniques they employ (Pérez-Marín et al., 2017a; Borges Pequeno et al., 2025).

Within this context, a range of collective action mechanisms has emerged (AS-PTA, 2017), including community seed banks, solidarity revolving funds, agroecological fairs, and GMO-free communities. These initiatives function as mechanisms for the co-production and management of common goods, governed by locally defined rules and supported by public policies. Mutual trust and community-based norms often regulate exchanges and ensure product quality more effectively than external bureaucratic controls.

The establishment of Participatory Conformity Assessment Bodies (OPACs) and Participatory Guarantee Systems (PGSs) represents a particularly significant institutional innovation, as these arrangements transfer part of the authority for quality assurance from centralized institutions to territorial networks of farmers and consumers operating in dialogue with the State, as exemplified by the ECOARARIPE network. Beyond certifying products, these mechanisms validate social relations grounded in trust, transparency, and shared responsibility, thereby challenging the dominant market-oriented and bureaucratic approaches to quality regulation.

More broadly, these arrangements constitute a notable experiment in participatory democracy applied to agriculture, contrasting with the clientelist practices and oligarchic forms of control that have historically shaped governance in the Semi-Arid Region. By creating spaces for shared decision-making and collective deliberation, they weaken traditional patterns of political dependence and foster new forms of active citizenship, social participation, and collective stewardship of the commons.

2.4. Gender and Youth

Agroecological experiences in the Semi-Arid region have highlighted the pivotal role of women farmers as custodians of native seeds, managers of productive home gardens, and leaders of local fairs and territorial networks. Studies indicate that women account for more than 58% of participants in seed networks and, in several regions, outnumber men in agroecological fair participation (CETRA, 2022). Beyond conserving biodiversity, women play a fundamental role in preserving cultural memory and facilitating the intergenerational transmission of knowledge (Agarwal, 2010).

This prominence extends beyond the productive sphere to encompass broader dimensions of power, agency, and social transformation. Through their management of revolving funds,

community seed banks, and participatory certification processes, women assume leadership positions and exert a direct influence on collective decision-making. This dynamic illustrates the convergence of agroecology and feminist perspectives, challenging historically entrenched patriarchal structures while fostering new forms of community leadership (Siliprandi, 2015). Agroecology not only promotes the diversification of production systems but also amplifies women's participation and influence in decision-making spaces that have traditionally been dominated by men.

At the same time, rural youth face the persistent challenge of outmigration driven by limited economic and social opportunities in rural areas. In response, initiatives such as community nurseries, beekeeping projects, popular communication networks, information and communication technologies (ICTs), and revolving funds have sought to engage young people by creating tangible opportunities for rural livelihoods and succession.

The retention and active participation of rural youth are essential for the intergenerational continuity of agroecological practices and for sustaining processes of sociotechnical innovation (Silva et al., 2020). By finding meaningful opportunities within agroecological systems, many young people are able to redefine their rural identities and envision viable futures in territories historically shaped by migration.

2.5. Political Economy and Territorial Markets

The economic sustainability of peasant agroecosystems depends on the effective articulation of self-consumption, territorial markets, and supportive public policies. Short food supply chains—such as agroecological fairs, the National School Feeding Program (PNAE), institutional procurement through the Food Acquisition Program (PAA), and community warehouses—constitute key mechanisms for securing household income, reducing dependence on intermediaries, and enhancing the value of local production (ASA, 2011; Petersen et al., 2017; Pérez-Marín et al., 2017a). Beyond their commercial function, agroecological fairs serve as important cultural, political, and social spaces where producers and consumers interact directly, reinforcing peasant identity, strengthening community networks, and fostering social trust.

From a political economy perspective, territorial markets represent more than alternative channels of commercialization; they are institutional arenas through which farming families seek to strengthen their economic autonomy and retain greater control over production and exchange processes. By shortening the distance between producers and consumers, these markets can contribute to more equitable value distribution and support locally embedded development strategies.

Nevertheless, the expansion of agribusiness and the increasing integration of agricultural production into global commodity markets impose significant constraints on the consolidation of territorial economies. The growing concentration of market power, coupled with the volatility of international prices, often undermines the economic viability of small-scale farming systems. This raises a critical question regarding the extent to which short marketing circuits can sustain resilient territorial economies, particularly in regions affected by recurrent droughts, climate variability, and external market shocks (IPES-Food, 2016).

As a result, peasant households operate within a persistent tension between the autonomy fostered through local market participation and the structural pressures that encourage their incorporation into longer and often unequal value chains. Understanding this tension is essential for assessing the transformative potential of territorial markets and the broader role they may play in promoting agroecological transitions and rural development.

2.6. Agroecology and Climate Justice

The related literature increasingly recognizes agroecology as a key strategy for both climate change mitigation and adaptation (Altieri, Nicholls, & Montalba, 2017; Bezner Kerr et al., 2023). In Brazil's Semi-Arid region, agroecological practices such as agroforestry systems, soil cover management, sustainable use of the Caatinga biome, and rainwater harvesting contribute significantly to carbon sequestration, water conservation, and the enhancement of productive resilience. By restoring ecological functions and improving natural resource management, these practices help transform degraded landscapes into productive and sustainable socio-ecological systems. Moreover, they strengthen food and nutrition security while fostering community cohesion and adaptive capacity in the face of increasing climate variability and extreme weather events (González de Molina, Guzmán, & Infante, 2019).

Beyond their environmental benefits, agroecological practices play a critical role in advancing climate justice by reducing the vulnerability of historically marginalized populations and creating conditions for dignified and sustainable livelihoods in environmentally fragile territories. This perspective highlights the intersection between ecological sustainability, social equity, and territorial development. In this sense, local agroecological experiences in the Brazilian Semi-Arid region are closely linked to broader international agendas, including the Sustainable Development Goals (SDGs), the Nationally Determined Contributions (NDCs) established under the Paris Agreement, and the objective of achieving Land Degradation Neutrality promoted by the United Nations Convention to Combat Desertification (UNCCD).

From this perspective, initiatives such as household cisterns, community seed banks, and agroforestry systems should not be viewed

merely as local development interventions. Rather, they represent tangible expressions of climate action and environmental governance that connect local communities to global efforts to address climate change, biodiversity loss, and desertification. Consequently, agroecology emerges not only as a technical and productive approach but also as a transformative socio-political project that contributes to building more resilient, equitable, and sustainable rural futures.

3. Methodological Approach

This article adopts an analytical–interpretive, qualitative, and interdisciplinary approach situated at the intersection of agroecology, ecological economics, and rural social sciences. Rather than undertaking an exhaustive statistical assessment, the study seeks to systematize and integrate empirical evidence from multiple agroecological experiences in the Brazilian Semi-Arid Region through the analytical lens of socio-ecological metabolism.

The research is based on a multiple-case study approach (Yin, 2015; Long & van der Ploeg, 2011), which enables the exploration of complex dynamics within specific contexts while identifying broader patterns and processes. The triangulation of diverse sources and scales of information strengthens the robustness of the findings and supports the development of a theoretical–methodological model that may be applied in future research. This methodological strategy seeks to engage with the diversity of local realities, respect community perspectives, and foster dialogue between scientific knowledge and social practice.

- Representative agroecological experiences from the Brazilian Semi-Arid Region were selected (van der Ploeg, 1993), combining family-based initiatives, territorial networks, and collective arrangements:

- Raimunda and Antônio Agroecosystem (Triunfo, Pernambuco) – documented by the Agroecological Development Center Sabiá (Centro Sabiá), this experience is characterized by a high level of self-consumption (approximately 90%) and the productive integration of orchards and agroforestry systems.

- ECOARARIPE Network (Pernambuco and Ceará) – a network that organizes farmers around participatory certification systems (OPAC and DACS), linking agroecological production to differentiated markets and public policies.

- Polo da Borborema / AS-PTA (Paraíba) – a well-established experience in the social construction of markets and collective mechanisms, including community seed banks, agroecological fairs, and revolving solidarity funds.

- Experiences of women farmers (CETRA, PATAC, and Casa da Mulher do Nordeste) – emphasizing women's participation in seed networks, agroecological markets, and feminist training processes.

- Rural youth initiatives – involving community nurseries, beekeeping, popular communication, and rural succession processes across different territories.

- "Recaatingamento" practices (IRPAA, Bahia) – focused on the restoration of the Caatinga biome as a strategy for ecological recovery and coexistence with semi-arid conditions.

- The selection of these cases (Long & van der Ploeg, 2011) was guided by three criteria:
- Socio-ecological relevance, defined as the capacity to generate significant impacts on biodiversity, water management, autonomy, market access, and social empowerment.
- Diversity of approaches, encompassing scales from individual households to territorial networks and including both productive practices and institutional arrangements.

- Availability of documented evidence, including technical reports, scientific publications, and materials produced by NGOs and agroecological networks.
- The analysis triangulated three principal sources of information:
- Institutional documents and systematizations: reports and publications produced by civil society organizations, including ASA, AS-PTA, Centro Sabiá, CETRA, IRPAA, and PATAC, describing methodologies, indicators, and outcomes.
- Scientific literature: peer-reviewed studies on agroecology in the Semi-Arid Region, with particular attention to the LUME methodology (Petersen et al., 2017; Borges Pequeno et al., 2025), analyses of desertification processes (Barbosa & Gallar Hernández, 2025; Pérez-Marín et al., 2022), and debates on socio-ecological metabolism (González de Molina & Toledo, 2023).
- Previously systematized qualitative data: interviews conducted through participatory action research projects, agroecological notebooks, and records of community exchanges.

The analytical framework was organized around six thematic axes derived from key gaps identified in both the literature and field experiences:

1. **Results and impacts:** integrated assessment of ecological, economic, and social outcomes.
2. **Scales and limits:** replication potential and institutional and ecological constraints.
3. **Metrics and indicators:** development of parameters that move beyond conventional productivity measures.
4. **Gender, power, and youth:** social impacts of women's and young people's participation.
5. **Governance and participatory democracy:** examination of collective arrangements and state–society co-management.
6. **Agroecology and climate justice:** contributions to mitigation, adaptation, and the prevention of desertification.

These axes are not merely analytical categories; they reflect tensions experienced daily by peasant families and constitute key interpretative dimensions for guiding public policy and future research.

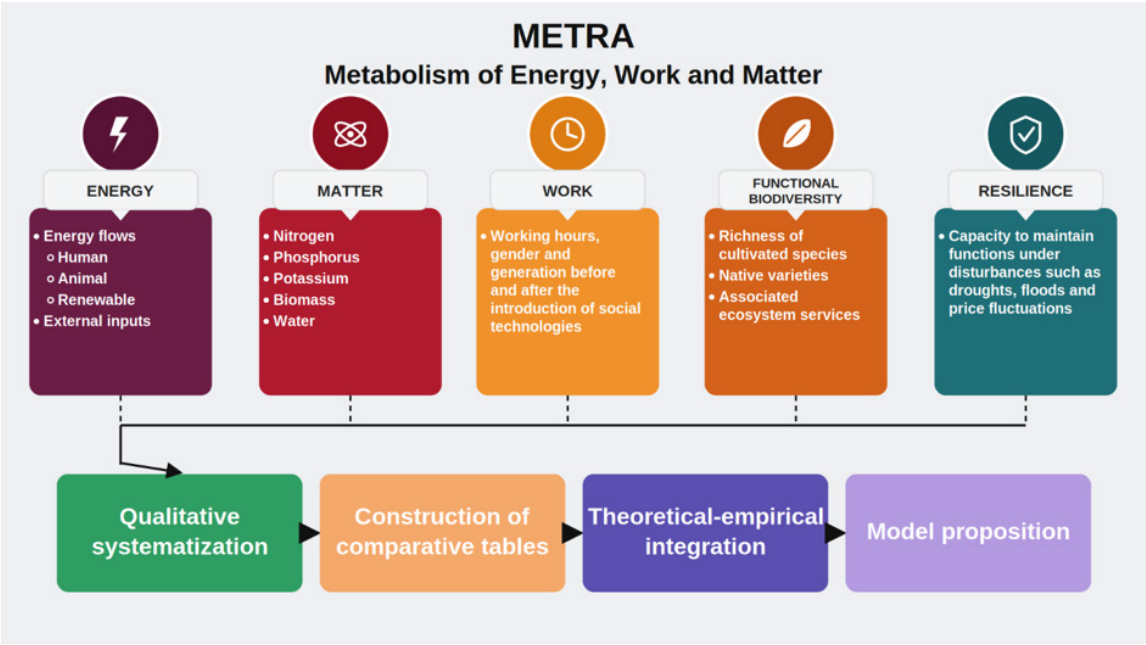
As an original methodological contribution, this article proposes the METRA model (Metabolism of Energy, Work, and Matter,

Figure 2), which integrates five dimensions:

1. **Energy (E):** human energy flows (working hours converted into MJ), animal and renewables; as well as energy embodied in external inputs.
2. **Matter (M):** nutrient balance (N, P, K), biomass and water, with emphasis on internal circularity.
3. **Work (T):** hours invested by activity, disaggregated by gender and generation, before and after the introduction of social technologies (tankers, revolving funds, among others).
4. **Functional biodiversity (B):** richness of cultivated species, native varieties and associated ecosystem services.
5. **Resilience (R):** ability to maintain functions (production, income, water availability) in the face of shocks such as droughts, floods or price fluctuations.

These dimensions allow the operationalization of socio-ecological metabolism in metrics applicable to the design and monitoring of public policies, the monitoring of the Sustainable Development Goals (SDGs) and the comparative evaluation between agroecosystems. METRA emerges as a tool to translate into numbers what families already experience in their daily lives, making visible processes invisible to conventional metrics.

Figure 2. METRA model: dimensions of socio-ecological metabolism in agroecosystems.



Note: The METRA model (Metabolism of Energy, Work, and Matter) operationalizes the concept of socio-ecological metabolism through five interrelated dimensions: Energy, Matter/Water, Work, Functional biodiversity, and Resilience. This framework makes it possible to translate agroecological practices into measurable indicators, rendering visible contributions that are frequently overlooked by conventional metrics, such as self-consumption, nutrient circularity, and the time savings generated by social technologies.

Source: Authors' estimates.

The analytical procedures combined several levels of systematization:

1. **Qualitative systematization:** identification of common patterns and context-specific dynamics across cases.
2. **Comparative synthesis:** development of comparative tables summarizing impacts and indicators, such as self-consumption, women's participation, and water storage capacity.
3. **Theoretical–empirical integration:** dialogue between empirical evidence and concepts related to socio-ecological metabolism, agroecology, and governance arrangements.
4. **Model development:** formulation of the METRA framework based on observed practices and the existing literature.

This analytical process was not solely an academic exercise. It also constituted a means of recognizing local knowledge and translating it into analytical frameworks capable of engaging with both scientific debates and public policy processes.

An illustrative application of the METRA model

To move the METRA model from proposal toward operationalization, we outline an illustrative application drawing on the ecological-economic dataset of Borges Pequeno et al. (2025), who applied the LUME method to 61 agroecosystem-based production systems (ABPS) across 44 municipalities of the Brazilian Semi-Arid. The LUME indicators map directly onto the METRA dimensions: the mobilization of internal versus external resources and the reuse of matter through reciprocity circuits (exchanges, donations, and stocks) express the matter and work dimensions; the Cultivated Biodiversity indicator (the number of species mobilized in production) expresses functional biodiversity; and the Autonomy attribute—the degree of governability achieved through economic-ecological reproduction strategies—expresses resilience. The energy dimension is not captured by monetary-ecological accounting alone and would require complementary biophysical indicators (e.g., water-storage efficiency and drought-response metrics), a limitation we return to below.

Each dimension can be read jointly with its economic translation. Economic value is expressed through Value Added (VA = Gross Income − Intermediate Consumption) and Monetary Profitability (MP = VA / Intermediate Consumption), that is, the value added recovered per unit of monetary cost invested, while the degree of agroecological reproduction is expressed through the Agroecologization Index (AI), modified so that values approaching 1 denote greater autonomy and reciprocity. Applied to the three system groups identified by Borges Pequeno et al. (2025), the framework discriminates contrasting metabolic-economic profiles (Table 1): Group 1 (≈10% of systems) combined high agroecologization (AI = 0.90) with high profitability (MP = 10.87)—about R$10.9 of value added per R$1 of intermediate cost—sustained by cyclic biomass reuse and high cultivated biodiversity; Group 3 (≈62%) reached moderate-to-high agroecologization (AI = 0.79) with modest profitability (MP

Table 1. Illustrative METRA reading of the three agroecosystem groups

METRA reading (LUME indicator)	**G1 (n = 6)**	**G2 (n = 17)**	**G3 (n = 38)**
Agroecologization Index (AI)	0.90	0.47	0.79
Monetary Profitability (MP)	10.87	0.72	2.37

Source: Adapted from Borges Pequeno et al., 2025.

= 2.37); and Group 2 (≈28%) showed low values on both (AI = 0.47; MP = 0.72), reflecting greater dependence on external inputs. Agroecologization and profitability were positively correlated (Spearman's $\rho = 0.56$, $p < 0.05$), and Autonomy contributed most to system performance in the multivariate analysis.

This worked example shows how METRA can translate energy–work–matter flows into a small set of indicators that are simultaneously biophysical, social, and economic, and commensurable with public-policy monitoring and the Sustainable Development Goals (notably SDG 11 and SDG 12). A full validation of METRA would extend this dataset with the energy dimension and apply the composite framework to a panel of agroecosystems over time.

Limitations of the Analysis

This article is based exclusively on secondary data compiled by social organizations and documented in previous research. No primary data were collected within the scope of this study. The available sources present considerable heterogeneity in terms of quality, methodological approaches, and comparability, which constrains the potential for robust quantitative generalization.

Furthermore, the proposed METRA model requires broader empirical validation across diverse socio-ecological contexts. Such validation should be undertaken through future field-based research to assess the model's applicability, reliability, and analytical robustness.

These limitations do not diminish the contribution of the present study. Rather, they highlight the need to strengthen collaborative efforts among academic institutions, public agencies, and community organizations in order to advance the socio-ecological assessment of agroecosystems in the Semi-Arid Region. Enhanced cooperation among these stakeholders will be essential for generating more comprehensive evidence and for supporting the design of sustainable territorial development strategies.

4. Critical Reflections from the Brazilian Semi-Arid

Rather than reporting primary experimental data, this section synthesizes and interprets evidence through a structured systematization of agroecological experiences in the Brazilian Semi-Arid. The sources—peer-reviewed studies, technical reports from civil-society organizations (notably ASA and AS-PTA), and datasets generated with the LUME method—were selected according to three criteria: thematic relevance to socio-ecological metabolism and agroecology in drylands, methodological transparency, and territorial representativeness across the Semi-Arid. Read together with the illustrative application of the METRA model and the ecological-economic indicators presented above, these reflections offer an analytical—rather than merely narrative—basis for informing territorial development pathways for semi-arid regions across Latin America.

The agroecological experiences of the Brazilian Semi-Arid Region, documented by civil society organizations and previous research, can be understood as living laboratories of socio-technical and institutional innovation (Altieri & Nicholls, 2012; Petersen et al., 2017; Pérez-Marín et al., 2017a; Borges Pequeno et al., 2025). Beyond their specific outcomes, these experiences reveal an alternative productive and territorial rationality that integrates ecological, economic, and social dimensions. Ecologically, practices such as productive home gardens, family agroforestry systems, and recaatingamento initiatives in degraded areas demonstrate the potential to regenerate the Caatinga through sustainable management, increasing soil organic matter, enhancing water infiltration, and reducing erosion (Stan, Sánchez-Azofeifa, & Calvo-Alvarado, 2019; Tabarelli et al., 2024; Borges Pequeno et al., 2025; Pérez-Marín et al., 2017a). Initially regarded as marginal practices, these initiatives have become important references for resilience, illustrating how agroecology can reconcile environmental conservation with social well-being in territories highly exposed to climate variability.

From an economic perspective, agroecology has strengthened household autonomy and diversified rural livelihoods (Batterbury, 2001). An illustrative example is the agroecosystem of Raimunda and Antônio in Triunfo, Pernambuco, where approximately 90% of household food consumption originated from on-farm production, significantly reducing monetary expenditures while enhancing food sovereignty (ASA, 2011; Petersen et al., 2017).

Agricultural surpluses were commercialized through short food supply chains—including agroecological fairs, community warehouses, and institutional procurement programs such as the National School Feeding Program (PNAE) and the Food Acquisition Program (PAA)—thereby providing income even during periods of drought when conventional value chains were disrupted (Silva et al., 2020). Similarly, solidarity revolving funds reduced dependence on formal credit arrangements and intermediaries, increasing households'

capacity to invest in productive infrastructure and technological improvements (Borges Pequeno et al., 2025). These experiences suggest that agroecology contributes not only to income generation but also to broader forms of economic resilience and autonomy.

Beyond these qualitative gains, ecological-economic accounting provides quantitative evidence of agroecology's economic performance. Using the LUME method across 61 systems in the Semi-Arid, Borges Pequeno et al. (2025) show that the economic contribution of an agroecosystem is best captured not by gross output but by Value Added—the new wealth produced once the cost of market inputs is deducted—and by Monetary Profitability, the value added recovered per unit of monetary cost.

The most agroecologized systems generated substantially higher returns (Monetary Profitability of about 10.9 in the highest-performing group versus 0.72 in the least agroecologized), indicating that reliance on internal, reciprocity-mobilized resources rather than purchased inputs raises, rather than lowers, economic efficiency. This is reinforced by the positive correlation between agroecologization and profitability ($\rho = 0.56$, $p < 0.05$), which challenges the conventional assumption of a trade-off between ecological soundness and economic return. Autonomy is therefore not only a social value but an economic strategy: by substituting non-market circuits for external inputs, families reduce their exposure to input-price volatility and stabilize income during drought years, when conventional value chains are most fragile. Social impacts have been equally significant. Dietary diversification and reduced reliance on agrochemicals have contributed to improvements in family health and nutrition (Altieri & Toledo, 2011; Bezner Kerr et al., 2021). Farmer-to-farmer exchanges and the use of agroecological notebooks have fostered horizontal learning processes that value local knowledge while facilitating the co-creation of innovations (Holt-Giménez, 2006; Petersen et al., 2017). In addition, the conservation of native seeds and traditional food practices has reinforced cultural identities and strengthened cultural and territorial sovereignty within the Semi-Arid Region (Martínez-Alier, 2008; CETRA, 2022).

The experiences also highlight the importance of socio-technical networks for scaling agroecology at the territorial level (Petersen et al., 2017; ASA, 2011). The ECOARARIPE network, for example, employs participatory certification mechanisms such as OPAC and DACS, which enhance the legitimacy of agroecological production and facilitate access to differentiated markets for family farmers. Community seed banks, solidarity revolving funds, and agroecological fairs function as social infrastructures that support the dissemination and replication of agroecological practices.

Nevertheless, important structural challenges remain. The reliance on family labor can constrain the expansion of labor-intensive agroecological systems, particularly during peak agricultural periods (Silva et al., 2020).

This limitation may increase dependence on intermediaries and weaken direct marketing strategies. Furthermore, discontinuities in technical assistance and rural extension services (ATER) restrict innovation processes, while pressures associated with global markets and the expansion of agribusiness create additional barriers to the consolidation of autonomous territorial economies (IPES-Food, 2016; Barbosa & Gallar Hernández, 2025).

Conventional agricultural performance indicators, such as yield per hectare or the monetary value of production, are insufficient to capture the multidimensional nature of agroecological systems (Astier et al., 2008; Martínez-Alier, 2008). In this context, the METRA model (Metabolism of Energy, Work and Matter) provides an innovative framework for operationalizing socio-ecological metabolism through five dimensions: energy, matter and water, labor, functional biodiversity, and resilience (Pérez-Marín et al., 2022; Borges Pequeno et al., 2025). These indicators make visible dimensions often overlooked by official statistics, including food self-consumption, labor savings generated by social water technologies, and production stability during drought periods (Power, 2010).

A notable feature of the experiences analyzed is the prominent participation of women and young people. In several agroecological networks, women account for approximately 58.5% of participants and play leading roles in revolving funds, participatory certification systems, and decision-making processes, thereby linking agroecology with feminist perspectives on rural development (Siliprandi, 2015; CETRA, 2022). Young people, meanwhile, engage in activities such as community nurseries, beekeeping, and grassroots communication initiatives, creating alternatives to rural outmigration despite the persistence of structural migration pressures (Silva et al., 2020; González de Molina et al., 2019).

Participatory governance emerges as another central dimension. Initiatives such as Participatory Guarantee Systems (PGS) and Participatory Conformity Assessment Bodies (OPACs) demonstrate that agroecological transitions depend not only on productive practices but also on innovative institutional arrangements (AS-PTA, 2017). These mechanisms facilitate market access, strengthen trust between producers and consumers, and enhance collective regulation of food quality, reflecting principles consistent with Ostrom's (1990) theory of the commons.

Finally, agroecology contributes to climate justice through both adaptation and mitigation pathways. Social water technologies and productive diversification have strengthened communities' capacity to cope with recurrent droughts, while agroforestry systems and Caatinga restoration initiatives have enhanced carbon sequestration in soils and biomass (Altieri & Nicholls, 2013; Pérez-Marín et al., 2017b, 2022; Borges Pequeno et al., 2025). Beyond these technical contributions, agroecology addresses structural inequalities by reducing the vulnerability of historically marginalized populations and linking

environmental sustainability with social justice. In this regard, the Brazilian Semi-Arid has emerged as an important international reference for policies promoting coexistence with semi-aridity and broader socio-ecological transitions (UNCCD, 2017; IPCC, 2023).

In summary, the agroecological experiences of the Brazilian Semi-Arid provide valuable insights for territorial development in Latin America and beyond. Ecologically, they demonstrate the potential for landscape regeneration; economically, they strengthen autonomy through self-consumption, territorial markets, and solidarity finance; socially, they highlight the transformative roles of women and youth; and politically, they illustrate innovative forms of participatory governance. By simultaneously advancing climate adaptation, mitigation, and social justice, these experiences offer relevant lessons for contemporary debates on sustainability, resilience, and inclusive territorial development.

5. Conclusions and Future Research Directions

The reflections presented in this article suggest that agroecology in Brazil's Semi-Arid region should be understood not merely as a set of productive techniques, but as a broader political-ecological project that integrates environmental conservation, social justice, and local autonomy. In territories historically shaped by structural inequalities and climate vulnerability, agroecological family farming has demonstrated its capacity to regenerate ecosystems, diversify livelihoods, increase household incomes, improve dietary diversity, strengthen cultural identities, and foster participatory forms of governance. Agroecology therefore represents more than an alternative production model; it constitutes a structural response to the intertwined environmental, social, and economic crises affecting rural territories.

Despite these achievements, significant challenges remain. Agroecological systems continue to depend heavily on family labor, while the discontinuity of technical assistance and rural extension services (ATER), increasing pressures from global markets, and the risk of institutional capture through clientelistic practices or agribusiness-oriented policy frameworks constrain their long-term sustainability (Silva et al., 2020; IPES-Food, 2016; Barbosa & Gallar Hernández, 2025). These limitations underscore the need for stable and long-term public policies, co-managed by state institutions and civil society organizations, capable of ensuring the continuity, scalability, and autonomy of agroecological transitions in the Semi-Arid region and across Latin America. This assessment points to several key areas for future research and policy development:

1. Scale and agroecological integrity: To what extent can agroecological networks expand without compromising their foundations in family labor, local knowledge, and endogenous resource use (Petersen et al., 2017)?
2. Transformative metrics: How can alternative evaluation frameworks, such as the METRA

model, be refined to measure autonomy, resilience, circularity, and social well-being beyond conventional productivity indicators (González de Molina & Toledo, 2023; Borges Pequeno et al., 2025)? In particular, future applications should complete the model's energy dimension by incorporating biophysical indicators—such as energy return on investment and water-storage efficiency—alongside the work and matter flows demonstrated here.

3. Gender and power relations: What are the long-term effects of women's participation in agroecological networks on power redistribution, political agency, and gender equity within rural communities (Siliprandi, 2015; CETRA, 2022)?

4. **Youth engagement and rural succession:** Which institutional, economic, and cultural arrangements are most effective in encouraging young people to pursue agroecological livelihoods and ensuring intergenerational continuity in rural territories (Silva et al., 2020)?

5. **Governance and participatory democracy**: How can state–society co-governance mechanisms be strengthened to prevent clientelist capture while reinforcing local autonomy and collective action (Ostrom, 1990; De la Cruz & Dessein, 2021)?

6. **Political economy and territorial markets:** Under what conditions can short food supply chains and territorial markets become the foundation of autonomous and resilient local economies capable of counterbalancing the influence of agribusiness (González de Molina, Guzmán, & Infante, 2019; ASA, 2011; IPES-Food, 2016)?

7. **Agroecology and global climate justice:** How can the contributions of agroecology be translated into measurable indicators recognized by international frameworks such as Nationally Determined Contributions (NDCs) under the Paris Agreement and the United Nations Convention to Combat Desertification (UNCCD) Land Degradation Neutrality targets (Altieri et al., 2017; Bezner Kerr et al., 2023; UNCCD, 2017; IPCC, 2023)?

In conclusion, this article does not present the findings of a conventional empirical study. Rather, it offers a critical and forward-looking reflection that synthesizes lessons from the Brazilian Semi-Arid region and projects them as valuable references for other semi-arid regions of Latin America and for broader global debates on sustainability and rural development (IPES-Food, 2016). In an era marked by escalating climate and socioeconomic crises, agroecology emerges not only as a strategy for living with semi-aridity but also as an ethical and political commitment to building more equitable, resilient, and sustainable territories.

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