

SOCIO-RURAL METABOLISMS OF MEZCAL IN THE QUERÉNDARO REGION, MICHOACÁN, MEXICO

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ABSTRACT

The analysis of the society-nature relationship helps us to understand complex socio-ecological systems and the basis for their sustainability. This study analyzes the components and relationships of the mezcal socio-ecosystem in the Queréndaro region, Michoacán, using the methodology of rural social metabolism, through collaborative work with local actors, based on semi-structured interviews and surveys. The results allowed the identification of three categories of metabolisms present in the region, observing that the traditional (C1) and traditional-hybrid (C2) metabolisms show greater self-sufficiency, socio-ecological profitability and connection with conservation; while the semi-industrial system (C3) presents greater economic benefits, although associated with increased negative externalities that affect productive diversification, sustainable resource use, and the preservation of traditional knowledge, cardinal elements that contribute to the sustainability of this socio-ecosystem. As elements for the sustainable management of the mezcal socio-ecosystem, the conclusion is that the conservation and diversification strategies of traditional rural social metabolisms (C1 and C2) are key for a better maintenance and balance between the basic dimensions of sustainability; while a tendency emerges towards the strengthening of specialized and technified metabolisms for mezcal production (C3), which should be regulated to avoid the increase of negative externalities that affect socio-ecosystems which provide natural resources and act in detriment of local biocultural knowledge.

Keywords: agricultural economics, environmental conservation, rural development, sustainability, traditional knowledge.

INTRODUCTION

Mexico has wide plant biodiversity and is characterized by having high presence of endemic species; particularly, for maguey species (*Agave spp*), there is evidence that Mesoamerican cultures cultivated and used them in different ways, for example, to produce fermented alcoholic beverages based on the sap of various maguey species (Colunga-García, 1996). In fact, the word *mezcal*

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comes from the Nahuatl *mexcalli*, cooked mezcal, from *metl*=maguey and *ixcall*=cooked (Colunga-García, 1996). It is a generic name used throughout Mexico to refer to alcoholic beverages obtained by distilling the sugars extracted from the stem and base of the maguey or agave; in fact, this also applies to tequila or mezcal made from *Agave tequilana* (Hernández, 2018).

Since the beginning of the 17th century, *Agave tequilana* has been highly exploited, generating processes of agricultural intensification, changes in land use, and substitution of relatively diverse germplasm by millions of genetically identical plants (Larson *et al.*, 2007). This (agro-industrial) social metabolism has led to low levels of sustainability in the way the exchange of matter, energy and information between the natural and social environments is organized (González de Molina and Toledo, 2014). Maintaining the tequilero production metabolism for the rest of the mezcals could imply alarming risks in relation to the diversity of mezcal magueys (Larson *et al.*, 2007), their landscapes and tradition in terms of culture and ancestral knowledge (Torres *et al.*, 2015a).

The potential socio-ecological effects of the trend towards agro-industrial production metabolisms have been widely reported by several authors, including Figueredo *et al.* (2014), Larson *et al.* (2007), Plascencia and Peralta (2018), Torres *et al.* (2015a), Torres *et al.* (2015b), Zizumbo-Villarreal *et al.* (2013), and Bautista (2020), who have identified the following as most relevant: (i) the change in land use due to land clearing for the establishment of monocultures; (ii) the decrease in inflorescence density, erosion and soil contamination by pesticides and herbicides; (iii) the reduction in water capture due to plant loss; (iv) the loss of wild and domesticated magueys; and, (v) the transformation of the traditional mezcal culture, as a result of its overexploitation and commodification, among others.

Therefore, it is necessary to rethink and plan how mezcal production can be managed towards greater degrees of sustainability, considering the current boom of this activity within the nine states of the Mexican Republic that already have the denomination of origin for mezcal: Durango, Guerrero, Guanajuato, Michoacán, Oaxaca, Puebla, San Luis Potosí, Tamaulipas and Zacatecas (Hernández, 2018).

The Official Mexican Standard NOM-070-SCFI-2016 recognizes only three types of this distilled beverage, based on their degree of purity (100% pure or mixed) and processing modality: ancestral, traditional and mezcal (the latter without additional adjectives, but in practice colloquially known as “technified”). Ramírez-Naranjo *et al.* (2024) made a characterization and classification of the various forms of mezcal production for the Queréndaro Region, Michoacán, under a socio-ecosystem approach that integrated ecological, economic, sociocultural and technological aspects. This classification found three

categories in the zone of interest: traditional, traditional-hybrid and semi-industrial.

The first two categories (traditional, traditional-hybrid) were characterized as systems that preserve the typical and ancestral traditions of the region; and that at the same time must coexist with other productive systems that are in transition to the industrial scale, such as the units in the semi-industrial category. The classification proposal, having a socio-ecosystem approach, not only integrated the technical variables of NOM-070-SCFI-2016, but also integrated other aspects such as economic diversification, cultural practices, and work time, among other relevant variables that allowed a broad understanding of the diversity of mezcal production systems for the study region.

Based on the above, the present study aims to estimate the society–nature relationship of the mezcal socio-ecosystem in the Queréndaro region, Michoacán, from the rural social metabolism approach. The study stems from the hypothesis that specialization and technification of rural social metabolisms in this mezcal socio-ecosystem are associated with an increase in negative socio-environmental externalities and the erosion of local biocultural knowledge, as part of the transition process towards an agro-industrial model oriented to international markets. The discussion of the results and conclusions from this study contributes to broadening the scientific dialogue towards the construction of more sustainable mezcal production socio-ecosystems.

THEORETICAL FRAMEWORK

The rural social metabolism approach makes it possible to represent how a society establishes the way it organizes the exchange of matter, energy and information with its natural environment (González and Toledo, 2014). This approach has been used as a theoretical basis for understanding the socio-environmental change resulting from the ecological crisis of modern society, and as a methodological tool for the analysis of the biophysical behavior of economies. In recent decades, this concept has been analyzed quantitatively and studies have been conducted, addressing topics as diverse as human health, development and economic growth, which are applied to both urban and rural issues (González and Toledo, 2014; Toledo and García-Frapolli, 2008). Analyses of social metabolism focused on the study of communities, municipalities and the rural context have taken on greater relevance in Latin America, where ecological and economic exchanges are articulated in specific territories.

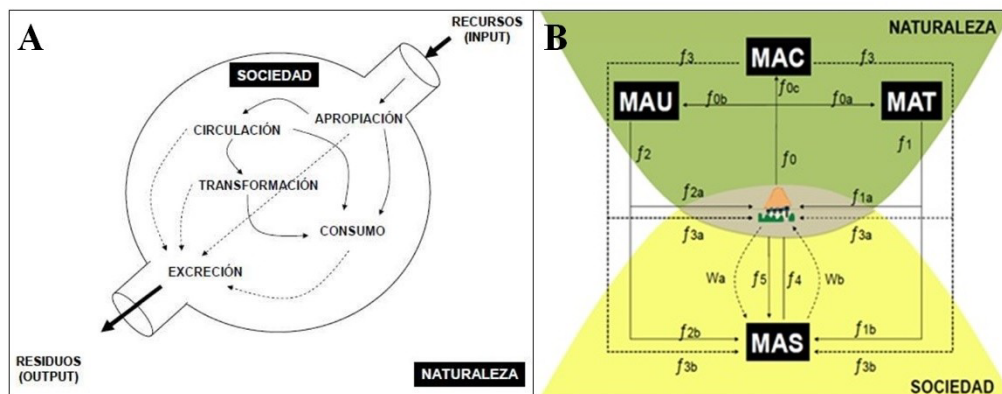
The base model of rural social metabolism, proposed by González de Molina and Toledo (2014), begins when an appropriation unit, individual, family, community, company, etc., performs the act of appropriating and transforming

ecosystems to meet their needs. In other words, it is the process through which, using their labor, human beings make a given amount of matter and energy transit from nature to their social space (González and Toledo, 2018).

This act of appropriation determines and is determined at the same time, by other processes that make up the basic model of social metabolism (Figure 1A). These are: transformation, physical or chemical change of the products appropriated from nature; circulation, process of exchange of transformed and untransformed products between appropriation units; consumption, process of satisfaction of the needs provided in the previous processes (appropriation, transformation and circulation); and, excretion, process through which matter and energy are thrown away into nature, which has no apparent value for the appropriation units that produce it (González and Toledo, 2014).

The rural social metabolism approach articulates each appropriation unit with four environments or universes of material interaction (González and Toledo, 2018). These environments are grouped into two main types: ecological and social.

Within the ecological environments, three subsets are distinguished: (1) Transformed Environment (TE), which corresponds to ecosystems that have been totally or partially modified by human activity; (2) Used Environment (UE), which refers to ecosystems that maintain their original structure, dynamics, and architecture, since human appropriation does not substantially alter their ecological functions; and (3) Conserved Environment (CE), which refers to areas designated for conservation, from which environmental services are obtained without significant direct intervention (González and Toledo, 2014).



Source: González de Molina and Toledo (2014).

Figure 1. A. The basic model of social metabolism. B. Flow model of rural social metabolism, TE (Transformed Environment, MAT in Spanish), UE (Used Environment, MAU in Spanish), CE (Conserved Environment, MAC in Spanish) and SE (Social Environment, MAS in Spanish).

The fourth environment is social in nature; it is the Social Environment (SE). This is configured in the process of circulation and exchange between different appropriation units. In other words, the SE represents the expanded social space, where the economic relations of the productive unit develop with other actors or broader social networks (González and Toledo, 2018).

METHODOLOGY

Study site

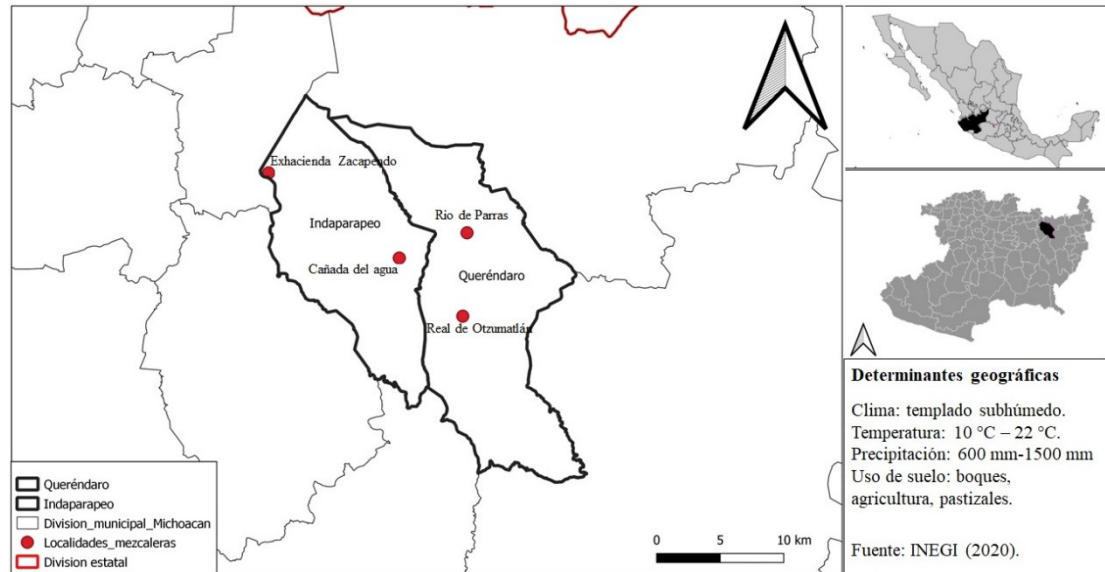
The mezcal-producing region of Queréndaro, in the state of Michoacán, Mexico, is composed of two municipalities. The municipality of Queréndaro has 13,836 inhabitants. Of these, 42.8% are part of the economically active population: 65.9% are salaried. The economic activity is distributed into the following sectors: primary (31.16%), services (30.85%), secondary (20.83%) and commercial (16.00%) (INEGI, 2020). For its part, Indaparapeo has a population of 16,990 inhabitants, of which 43.72% are economically active: 62.95% are salaried and 36.52% non-salaried. Economic activities by sector are secondary (36.06%), services (26.10%), primary (19.89%) and commercial (17.34%) (INEGI, 2020).

There are four mezcal-producing localities in these municipalities: Río de Parras, Real de Otzumatlán, Cañada del Agua and Exhacienda Zacapendo (Figure 2). These localities currently produce mezcal using wild maguey species such as *Agave inaequidens* (tall or criollo), and other cultivated species such as *Agave cupreata* (chino), and *Agave tequilana* (chato or azul) (Ramírez-Naranjo *et al.*, 2024).

Method

The key elements and processes of rural social metabolism were identified. First, sixteen semi-structured interviews were conducted with mezcal-producing families in the study region. Second, participatory activities were carried out with local actors (participant observation) during eight working days. Third, the interviews and participant observations were transcribed and inductively coded, using Atlas.ti 8.4 software, by linking the codes to the landscape spaces identified in González and Toledo (2014), and methodologically explained in Toledo and García-Frapolli (2008), as shown in Figure 1B. Thus, the activities corresponding to each of the flows of the metabolic structures present in the mezcal production socio-ecosystem for the study region were identified (Table 1).

Fourth, the metabolic structures for each of the categories proposed by Ramírez-Naranjo *et al.* (2024) were constructed quantitatively. Due to factors



Source: prepared by the authors with data from INEGI (2020).

Figure 2. Location of the mezcals socio-ecosystem, Queréndaro region, Michoacán.

such as the effort required in terms of logistics, time and money to quantify the metabolic flows, it was decided to work with a non-probabilistic sample, with two representatives per category, according to the classification made by Ramírez-Naranjo *et al.* (2024); that is, traditional, traditional-hybrid and

Table 1. Metabolic flows in the study region.

Landscape spaces	Flows	Sub-flows	Activities
TE	F_0	F_{0a}	Amount of money in hours devoted to care, inputs used, harvesting cultivated maguery and other crops.
UE		F_{0b}	Amount of money in hours devoted to extracting wood (firewood), resins, or harvesting wild maguery.
CE		F_{0c}	Amount of money in hours devoted to forest care, technical assistance, research and ecotourism.
TE	F_1	F_{1a}	Cash value of appropriated household consumption goods.
		F_{1b}	Sale of mezcals from cultivated maguery.
		F_{1c}	Sale of other crops or other goods (mezcals creams).
UE	F_2	F_{2a}	Value of wood used in the production unit.
		F_{2b}	Sale of mezcals from wild maguery.
		F_{2c}	Sale of wood.
CE	F_3	F_{3a}	Value of environmental services.
		F_{3b}	Value of environmental services.
SE	W	W_a	Value of independent work.
		W_b	Value of hired work.

Source: prepared by the authors based on the analysis developed in Atlas.ti 8.4.

semi-industrial. Four field visits of one to two days each were made to the six selected production units (24 field visits in total).

The quantification of metabolism flows was done through a survey with the head of household. The selection criteria for the representatives by category were: seniority; level of accessibility to the data; level of trust with the head of household, which is important, since the data requested for metabolism mapping require researcher-producer trust, insofar as the information provided is personal and confidential and, ultimately, representative of the category.

In cases where the producer did not have any of the required data or flows, measurements and calculations were made in the field, through scheduled visits, which was the common denominator in most of the metabolic flows. Once the metabolic flows of the two production units per category were obtained, the metabolic values or flows were weighed to obtain an approximate average value per category. To standardize the information and compare the three categories analyzed, all data were converted to Mexican pesos per year (MNX/year), as estimated costs of the metabolic flows summarized in Table 1. Finally, the integration of results was done (Table 2), under the indicators of rural social metabolism proposed by González and Toledo (2018).

Table 2. Indicators of rural social metabolism.

Indicator	Description	Equation	Interpretation
Economic benefit	It is calculated as the difference between the sum of flows from nature to the family unit and society and the sum of flows from society and the family unit to nature.	$(F_1 + F_2 + F_3) - (F_0 + W_b)$.	It allows identifying whether the metabolism is generating surpluses (benefits) of money or time.
Economic profitability	It is calculated as the quotient between the economic benefit indicator and the flows that leave the family unit towards nature.	$((F_1 + F_2 + F_3) * (F_0 + W_b)) / F_0$	It allows to determine the percentage of profitability in money or time, when nature is appropriated.
Monetary balance	This indicator is calculated as the difference between the flows from the social environment to the family unit and the flows from the family unit to the social environment.	$(F_4 + W_a) - (F_5 + W_b)$	It allows to identify if the production unit earns money or if, on the contrary, the system requires money or labor from the outside.
Economic self-sufficiency	This indicator is the representation in percentage of products extracted from nature that are destined for self-consumption, among the total value of products or resources flowing into society.	$((F_{1a} + F_{2a} + F_{3a}) / ((F_1 + F_2 + F_3)))$	The higher the percentage, the greater the amount of resources that remain in the production unit for self-consumption and therefore self-sufficiency is prioritized over markets.

Source: prepared by the authors based on the proposed indicators from González y Toledo (2018).

RESULTS

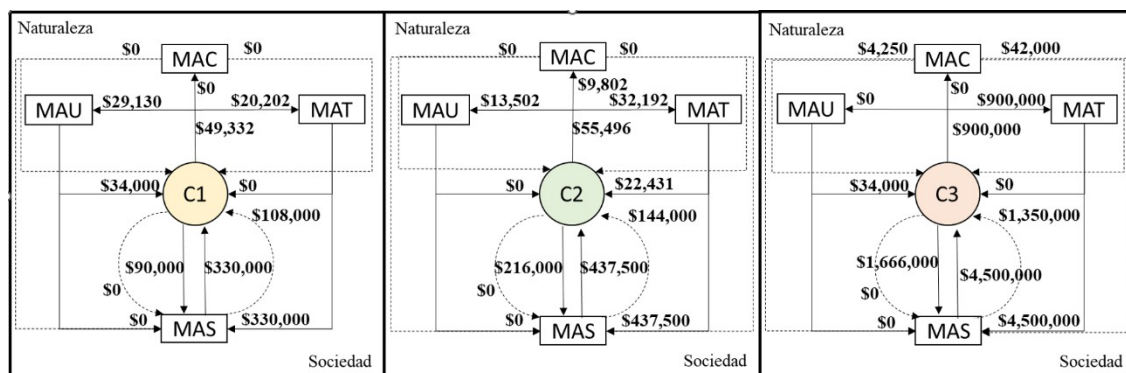
The metabolism of the mezcal-producing socio-ecosystem in the Queréndaro region constitutes a complex network of relationships between production units (producer families) and the surrounding socio-natural environment. Figure 3 presents the metabolic structures for each analyzed category, which will be discussed below along with their corresponding economic-ecological indicators.

Metabolism structures per category

C1 (Traditional production unit): In the case studies within this category, the production units extract firewood from the Used Environment (UE) for self-consumption and to partially meet the demands of the mezcal cooking and distillation process, representing an estimated value of \$34,000 MXN/year. At the same time, they harvest wild agave hearts (*Agave inaequidens*), which represent an income of \$150,000 MXN/year from mezcal sales.

These activities require an investment of \$19,202 MXN/year (1,080 hours/year) of labor for forest-related tasks (mainly tree felling and harvesting of wild agave), as well as \$10,000 MXN/year in inputs such as gasoline for transport, tool maintenance, care of donkeys, among others.

From the Transformed Environment (TE), the family production units extract cultivated agave hearts (*A. inaequidens* and *A. cupreata*), generating an average income of \$180,000 MXN/year from mezcal sales. These activities require a labor investment of \$10,202 MXN/year (approximately 576 hours/year), along with an estimated \$10,000 MXN/year in inputs.



Source: prepared by the authors.

Figure 3. Average mezcal metabolic structures in the Queréndaro region. C1: Traditional production unit; C2: Traditional-hybrid production unit; C3: Semi-industrial production unit.

Regarding the relationship between the appropriation unit and the Conserved Environment (CE), it is unidirectional, insofar as the production units indirectly benefit from the CE, through ecosystem services such as air and water; however, in this specific case, the units do not receive or return any flow specifically, such as forest conservation efforts, forest use for ecotourism, or payment for environmental services.

Finally, the relationship between the family appropriation units and the Social Environment (SE) is bidirectional: on the one hand, there is an inflow of \$330,000 MXN/year from mezcal sales, and on the other hand, there are two outflows of \$90,000 MXN/year and \$108,000 MXN/year for household goods and services and payment of hired labor, respectively (Table 3).

C2 (Traditional-hybrid production unit): In the case study for this category, the production units extract wild agave hearts (*Agave inaequidens*) from the Used Environment (UE), generating an average income of \$125,000 MXN/year from mezcal sales. These activities require an investment of \$8,502 MXN/year (480 hours/year of labor) for the care and extraction processes in the forest (mainly tree falling and harvesting of wild agave), as well as \$5,000 MXN/year in inputs such as gasoline for transportation, tool maintenance, care of pack animals, among others. From the Transformed Environment (TE), the family production units extract cultivated agave hearts (*A. inaequidens*, *A. cupreata*, and *A. angustifolia*),

Cuadro 3. C1 metabolism structure (traditional).

Flows	Activities	Average cost (MX/Year)
F _{0a}	Hours and inputs devoted to cultivated maguey	20,202
F _{0b}	Hours and inputs devoted to wild maguey	29,130
F _{0c}	Forest care	0
F ₀	Sum F _{0a} + F _{0b} + F _{0c}	49,332
F _{1a}	Family consumption (crop or livestock breeding)	0
F _{1b}	Sale of cultivated mezcal	180,000
F ₁	Sale of wild mezcal	150,000
F ₁	Sum F _{1a} + F _{1b}	330,000
F _{2a}	Value of extracted wood	34,000
F _{2b}	Sale of wood	0
F ₂	Sum F _{2a} + F _{2b}	34,000
F _{3a}	Income and hours dedicated to ecotourism	0
F _{3b}	Value of scientific and technical assistance	0
F ₃	Sum F _{3a} + F _{3b}	0
F ₄	Sum F _{1b} + F _{2b} + F _{3b}	330,000
F ₅	Clothing, food, education, energy, etc.	90,000
W _a	Freelance work	0
W _b	Hired workers	108,000

Source: prepared by the authors.

generating an average income of \$312,000 MXN/year from mezcal sales. These activities involve an investment of \$17,004 MXN/year (960 hours/year) in labor for care and extraction, and \$12,000 MXN/year in inputs. The units also produce foods such as peaches, pears, lettuce, avocado, eggs, fish, chicken, etc., grown and raised by the production units in a home garden for self-consumption. This production represents a market value of \$22,431 MXN/year and requires an estimated labor investment of \$3,188 MXN/year (180 hours/year).

Regarding the relationship with the Conserved Environment (CE), the family invests 384 hours/year (valued at \$6,802 MXN/year) in forest care and conservation activities—mainly reforestation with pine and oak—along with \$3,000 MXN/year in inputs and seedlings. These efforts aim to secure the long-term provision of environmental services from this landscape unit, particularly water supply. In this case, the family does not receive payments for environmental services nor use the forest for ecotourism.

Finally, the relationship between the family appropriation units and the Social Environment (SE) is bidirectional: on the one hand, there is an inflow of \$437,500 MXN/year from mezcal sales, and on the other hand, there are two outflows of \$216,000 MXN/year and \$144,000 MXN/year for household goods and services and payment of hired labor, respectively (Table 4).

Table 4. C2 metabolism structure (traditional-hybrid).

Fluxes	Activities	Average cost (MNX/Year)
F _{0a}	Hours and inputs devoted to cultivated maguery	32,192
F _{0b}	Hours and inputs devoted to wild maguery	13,502
F _{0c}	Forest care	9,802
F₀	Sum F0a + F0b + F0c	55,496
F _{1a}	Family consumption (crop or livestock breeding)	22,431
F _{1b}	Sale of cultivated mezcal	312,500
F _{1b}	Sale of wild mezcal	125,000
F₁	Sum F1a + F1b	459,931
F _{2a}	Value of extracted wood	0
F _{2b}	Sale of wood	0
F₂	Sum F2a + F2b	0
F _{3a}	Income and hours dedicated to ecotourism	0
F _{3b}	Value of scientific and technical assistance	0
F₃	Sum F3a + F3b	0
F₄	Sum F1b + F2b + F3b	437,500
F₅	Clothing, food, education, energy, etc.	216,000
W _a	Freelance work	0
W_b	Hired workers	144,000

Source: prepared by the authors.

C3 (Semi-industrial production unit): In the case studies within this category, the focus was on a production unit in which the family unit is not directly involved in the socio-ecosystem described. As such, this metabolic structure does not extract any resources directly from the Used Environment (UE).

Meanwhile, from the Transformed Environment (TE), the production units extract all the agave hearts (*Agave cupreata* and *Agave tequilana* var. azul), generating an average income of \$4,500,000 MXN/year from mezcal sales. The unit invests around \$900,000 MXN/year in inputs—mainly fertilizers and pesticides—since no family member contributes time to the operation for any activity beyond administrative tasks.

Regarding the relationship with the Conserved Environment (CE), the unit receives an average income of \$42,000 MXN/year from ecotourism and \$4,251 MXN/year in technical advisory services provided by the entity that certifies their beverages.

Finally, the relationship between the family appropriation unit and the Social Environment (SE) is bidirectional: on the one hand, there is an inflow of money from mezcal sales, and on the other, two outflows of \$1,666,000 MXN/year and \$1,350,000 MXN/year, corresponding to payments for inputs and factory maintenance, and salaries for employees, respectively (Table 5).

Table 5. Metabolism structure C3 (semi-industrial).

Fluxes	Activities	Average cost (MNX/Year)
F _{0a}	Hours and inputs devoted to cultivated maguey	900,000
F _{0b}	Hours and inputs devoted to wild maguey	0
F _{0c}	Forest care	0
F₀	Sum F0a + F0b + F0c	900,000
F _{1a}	Family consumption (crop or livestock breeding)	0
F _{1b}	Sale of cultivated mezcal	4'500,000
F _{1c}	Sale of wild mezcal	0
F₁	Sum F1a + F1b	4'500,000
F _{2a}	Value of extracted wood	0
F _{2b}	Sale of wood	0
F₂	Sum F2a + F2b	0
F _{3a}	Income and hours dedicated to ecotourism	42,000
F _{3b}	Value of scientific and technical assistance	4,251
F₃	Sum F3a + F3b	46,251
F₄	Sum F1b + F2b + F3b	4'500,000
F₅	Clothing, food, education, energy, etc.	1'666,000
W _a	Freelance work	0
W_b	Hired workers	1'350,000

Source: prepared by the authors.

Metabolism structures per category – case studies

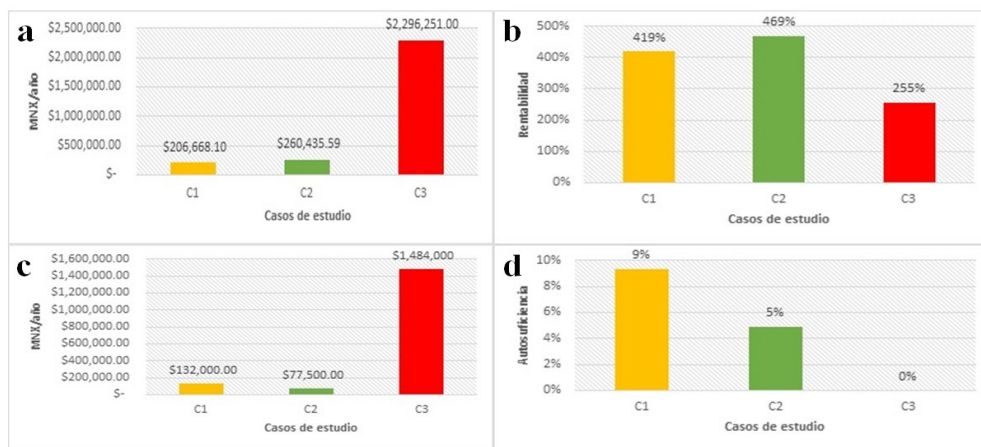
The indicators of rural social metabolism for the three categories studied were estimated based on the flows previously defined in the methods section and are presented in Figure 4.

I1 (Economic-ecological benefit): This indicator corresponds to the difference between the income received by the family production unit from mezcal sales and the monetary investment made by the production unit in landscape units (CE, UE, TE) due to time and input usage. It was calculated for each category as $(F1 + F2 + F3) - (F0 + Wb)$, Figure 4a.

For this indicator, the benefit arises from the difference between the income received by producers and their investment in labor hours and inputs. This reveals whether the systems are economically efficient, insofar as higher income with lower investment in resources and labor time implies greater efficiency. Desirable results for this indicator align with the following trend: the higher the indicator value, the greater the economic utility.

However, it is important to consider that a higher economic utility does not always correlate positively with impacts on the landscape unit that is being appropriated. Thus, a balanced relationship between these aspects should be considered. Generally, increased care for the landscape unit could imply a reduction of economic profits but generate greater positive environmental impacts.

When analyzing results by category, C3 exhibited higher economic utility than the categories C1 (traditional) and C2 (traditional-hybrid). This is due to the



Source: prepared by the authors.

Figure 4. Social metabolism indicators. a: Economic-ecological benefit (I1); b: Economic-ecological profitability (I2); c: Economic-ecological flows balance (I3); and d: Economic-ecological self-sufficiency (I4).

amount of liters of mezcal produced, where C3 produces approximately five times more than C1 and C2. Additionally, C1 and C2 interact with all three landscape units (UE, TE, CE), investing time and inputs in care and extraction of resources, while C3 interacts only with TE, externalizing resources indirectly used from UE and CE, such as water, air and foods it consumes.

I2 (Economic-ecological profitability): This refers to the profit or loss rate generated by each landscape unit, weighed against the hours, inputs, and hired labor invested by families per unit. It was calculated as $[(F1 + F2 + F3) - (F0 + Wb)] / F0$, with category-specific values shown in Figure 4b.

Accounting for family and hired labor costs, the landscape units allowed producers to get economic profitability in all three categories (C1, C2, C3). However, profitability was higher for C2 and C1, increasing with better utilization of the diversity of resources (better appropriation by producers), among them fruits, vegetables, animals, timber for self-consumption, and wild agave harvesting.

Additionally, C2 and C1 did not require high investment destined to hired labor, as the entire family engages in appropriation processes of landscape units. In contrast, this did not happen in C3, since there is no direct participation in the appropriation processes due to its focus on commercial and administrative activities. Furthermore, C3 invests significantly in fertilizers and pesticides, while C1 and C2 do not. This explains why family appropriation units in categories C1 and C2 achieved higher profitability from the resources they extract and exploit from nature.

I3 (Economic-ecological balance): This indicator shows the difference between monetary inflows and outflows in the family appropriation unit and the SE. The income received from mezcal sales or other activities was quantified (Figure 4c), and the cost of inputs and additional labor was subtracted. It is important to highlight that this indicator includes the monetary value of food that the family appropriation unit provides the family for self-consumption, which was calculated through: $(F4 + Wa) - (F5 + Wb)$.

In sum, the flows in this indicator allowed evaluating the capacity of each type of family appropriation unit to generate money, so a positive value implies profit. As shown in Figure 4c, all three categories yielded monetary gains, but C3 vastly outperformed C1 and C2 annually. This is attributed to: the high mezcal production volume in liters by C3, which is up to 400% higher than C1 and C2. Something else to consider is the average sale value (price) per liter of mezcal, which is 80% higher than C2 and double that of C1. These factors also explain why C2 was the category that had the lowest profits.

I4 (Economic-ecological self-sufficiency): This indicator measures the degree of self-sufficiency within production units. With higher percentage, it can

be interpreted that there is greater allocation of workdays, money, and food toward production and sustaining the family production unit. Conversely, lower values indicate that products are primarily destined for the rest of society. In other words, high values show that self-sufficiency is prioritized over market exchanges, and vice versa. The calculation is: $(F1a + F2a + F3a) / (F1 + F2 + F3)$.

Overall, the three cases exhibited low self-sufficiency levels (Figure 4d). This is primarily linked to the high dependence of the three study cases on a specific type of raw material, agaves, whether wild or cultivated; ultimately, these are processed into mezcal and predominantly sold to the market. Limited practices were observed in species regeneration or agricultural techniques (e.g., cultivation, breeding) aimed at enhancing and increasing self-consumption by these enterprises in the region. In fact, C3 showed no self-sufficiency.

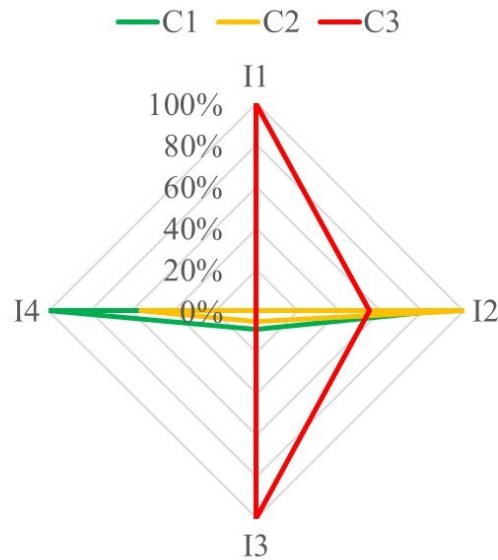
In the case of C1, the self-sufficiency value was higher than C2, as C1 sources a significant portion of firewood for mezcal cooking and distillation (nearly half its demand) from the UE, without direct forest conservation processes. In contrast, C2 has implemented reforestation efforts in the CE and presently no longer extracts wood from any landscape unit directly. Instead, its wood demand is fully met through purchases from regional sawmill market suppliers, which is similar to the case of C3.

Integration of indicators: the metabolisms of the different categories exhibit distinct behaviors, as illustrated in Figure 5.

The representation of the metabolism of C3 stands out due to its distinct behavior. This category exhibited trends toward agro-industrialization, clearly contrasting with the divergent structures observed in categories C1 and C2, which represent more traditional metabolisms. A striking trend in C3 is its emphasis on increasing indicators related with rentier benefits for the appropriation unit (I1) and economic efficiency (I3). This is because of its market-driven economic orientation, in contrast to C1 and C2, which are characterized by more traditional, pluralistic economic processes. Consequently, C1 and C2 demonstrate more positive indicators for self-sufficiency (lower dependence on market economies) and socio-ecological profitability (benefits for both nature and producer families).

DISCUSSION

The rural metabolisms of the traditional mezcal socio-ecosystem in the Queréndaro region are complex systems, where diverse interactions converge. The units studied exhibited differences across categories (C1, C2, C3), yet clear clustering patterns also emerged within categories, based on their relationships with society and nature. In this sense, it was identified that among the three



Source: prepared by the authors.

Note: For the integration of indicators, data normalization was conducted (scaling the highest value to 100%), to standardize and visualize the information effectively.

Figure 5. Radial integration of indicators for mezcal social metabolism.

coexisting metabolic types in this territorial space, two of them (C1 and C2) are closely aligned, while one is considerably distant from the others (C3).

The divergence observed in category C3 is associated to its specific relationship with nature, production that is quite close to what is known as agro-industrial, generating greater economic benefits but leading higher ecological and sociocultural negative externalities (Delgado-Lemus *et al.*, 2014; Figueredo *et al.*, 2014; Plascencia and Peralta, 2018; Torres *et al.*, 2015). This stems from the amount and frequency of extraction of natural resources (CE, UE, TE) by C3, contrasting with C1 and C2, which maintain a more reciprocal relationship with nature, through inflows and outflows; that is, just as resources are extracted, some conservation and ecological care actions take place (Figure 3). This condition defines the essential difference between traditional producer categories (C1 and C2) and the semi-industrialized, unbalanced metabolism of C3.

Regarding this, recent studies (Cuervas *et al.*, 2019; Espejel *et al.*, 2019; García-Benítez *et al.*, 2024; Ramírez-Naranjo *et al.*, 2024) address Mexico's mezcal socio-ecosystem but lack the theoretical-methodological lens of rural social metabolism. However, parallels exist with research on other types of rural systems, such as studies by Blanco (2015), García-Frapolli *et al.* (2008),

González and Toledo (2018), Guzmán and González (2008), Ortiz-Avila and Masera (2008), Tello *et al.* (2019), and Zuberman and Fernández (2016).

These studies generally agree with this study in: (i) order and coherence of the different methodological activities, measuring exchange flows and obtaining mean values; (ii) the way of identifying and measuring producer effort (labor) in each productive activity; (iii) identification of goods and services, derived both from self-sufficiency-derived and the market-derived; and (iv) the measurement unit used, monetary value of each productive practice, and productive efficiency calculated as the ratio between labor input and monetary return flow.

Based on the above, this research established a metabolic profile or structure for the comprehensive analysis of resources appropriated by a community, understanding which resources are consumed, transformed, or sold as commodities, alongside services provided (e.g., ecotourism, gastronomic, commercial, field support, etc.) and the workforce they occasionally sell. Notably, similarities were observed with García-Frapolli *et al.* (2008), who analyzed Mayan rural communities in the Yucatán Peninsula. Like the rural mezcal communities of Queréndaro, these groups invest the smallest portion of their labor effort in generating goods and services for self-sufficiency, dedicating most of the time and resources to producing market-oriented goods and services.

This highlights the current position of rural communities as sites transitioning toward the commodification of their bioculturality, thereby becoming dependent on market forces to sustain themselves as family production units. Their dynamics differ ecologically, socially, and economically, as was corroborated by García-Benítez *et al.* (2024) in their analysis of the artisanal mezcal production system in Puebla. These communities remain at a clear disadvantage compared with systems designed to operate in highly competitive global markets, which tend to disregard the value of tradition beyond whether it is good business or not (Plascencia and Peralta, 2018).

A comparative analysis between three rural forest producer types in Ejido Casas Blancas, Michoacán (Ortiz-Avila and Masera, 2008) and the results from this study also revealed an inverse pattern to that observed in the traditional mezcal socio-ecosystem metabolism. In their study, the most diversified category of forest producers (agrosilvopastoral) exhibited the highest economic efficiencies, in contrast to what could be observed for the Queréndaro region, where the most diversified categories (C1 and C2) showed the lowest economic balance and efficiency indicators.

This disparity can be attributed to the regulatory and market dynamics of mezcal sale, which prioritize certified producers, who command higher prices

and better access to a demanding global market; this international market has a very distinct perception of the product compared to domestic markets. International buyers are often willing to pay premium prices for mezcal, given its uniqueness and niche accessibility. Additional advantages, such as foreign exchange benefits, further amplify this trend, aspects also mentioned by García-Benítez *et al.* (2024).

On the other hand, the studies mentioned before by Ortiz-Avila and Masera (2008) and García-Benítez *et al.* (2024) identify how national and federal policies are steering diversified rural peasant forest systems toward the configuration of increasingly specialized models. This shift could negatively impact agrobiodiversity, generating a loss of it and reducing the self-sufficiency of producer families; this situation is also faced by the traditional mezcal socio-ecosystem in the Queréndaro region. These findings underscore the urgent need to reevaluate national policies governing traditional mezcal production, including frameworks like the Mezcal Designation of Origin (*Denominación de Origen Mezcal*).

Finally, González and Toledo (2018) and Torres and Valencia (2018) analyzed the economic-ecological indicators of rural social metabolism in Colombian coffee systems across different categories. Comparing their results with those of this study, in terms of the indicators of economic-ecological benefit and economic-ecological balance, confirms the trend that the categories with agro-industrial metabolisms present greater economic benefits, in contrast to those closer to traditional metabolisms.

Regarding the indicator of economic-ecological profitability compared to other crops, results differ between the coffee producing system and the mezcal systems in Queréndaro. In peasant coffee systems, profitability is negative for all cases, primarily due to coffee's dependence on volatile global market prices. Therefore, the indicator is not comparable at any level between the two systems. However, it is noteworthy that for all the studies compared, the profitability percentage is low for industrial/enterprise-oriented production systems, largely due to the internalization of the monetary value of family labor in peasant/traditional systems, a pattern also noted by González and Toledo (2018).

In terms of the indicator of economic-ecological self-sufficiency, results are consistent across all compared studies for enterprise-oriented systems, with very low percentages nearing zero. In contrast, for the case of traditional mezcal socio-ecosystems in the Queréndaro region, there is concern, as its self-sufficiency levels are significantly lower than those of their counterpart systems compared. This reinforces uncertainties about a potential shift from traditional mezcal metabolism toward agro-industrial metabolisms, situation

previously highlighted by García-Benítez *et al.* (2024) and corroborated by this research.

CONCLUSION

The metabolic processes of rural mezcal socio-ecosystems in the Queréndaro region exhibit a gradient of sustainability, ranging from higher to lower, depending on the characteristics of the three categories (that is, metabolic structures) described here. In this sense, the semi-industrial category (C1) maintains a utilitarian relationship with nature, generating greater rentier benefits, but at the expense of externalizing care and conservation relationships with the landscape units it interacts with.

This condition establishes a critical divergence between traditional-hybrid (C2) and traditional (C1) production categories, leading to divergent exchanges in the appropriation, transformation, and commercialization of mezcal with nature and society, despite their coexistence in the same region. This fosters a trend toward the commercial transition of traditional production systems, which cannot compete on equal terms within a free market that disregards their historical and biocultural fabric.

Without clear institutional safeguards, it is foreseeable that the commodification of traditional knowledge, the degradation of natural resources, and therefore, the unsustainability of the region's mezcal metabolism will likely escalate. Nevertheless, the mezcal socio-ecosystem resists full commodification through certain metabolic relationships in the traditional and hybrid categories.

Thus, key strategies for resilience and which can contribute to a more sustainable management of this complex socio-ecosystem include: strengthening the knowledge, use and conservation of the resources appropriated, which have historically benefited units rooted in traditional practices (C1 and C2), that is, emphasizing care and protection of nature, an area where academic institutions play a vital role in revaluing these practices.

Additionally, it is essential to promote productive diversification as a key factor that balances metabolic inflows and outflows, which strengthen sustainability of the socio-ecosystem, to the extent that traditional family units, in addition to the production and sale of mezcal, engage in plural economies (for example, backyard gardens for self-consumption and neighborly exchange of goods and services, household and solidarity-based economies). These forms of metabolic relationships understand that over-specialization and depending solely on mezcal production heightens vulnerability for both ecosystems and traditional knowledge.

It is important to note that this study has two concrete limitations: first, measuring metabolisms based on socio-ecological indicators from a single

framework, excluding broader sustainability metrics (a focus for future work); second, since sampling is non-probabilistic, the results only allow identifying general trends to describe the cases or contexts of producers in the region of study, and therefore, quantitative studies using probabilistic sampling are recommended. It is important to highlight that the results observed in the units analyzed in this study are specific to each metabolism; that is, it cannot be inferred that a unit is sustainable or not simply because it belongs to a specific category.

Finally, this work opens new lines of research associated to strategies for territorial resource management that are complementary and integral to mezcal production, leaving the door open to experiences such as agroforestry and even strengthening and developing forms of alternative economy, such as household, solidarity-based, feminist and popular economies.

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