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Sociometabolic research in Latin America: A review on advances and knowledge gaps in agroecological trends and rural perspectives

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ABSTRACT

Current agricultural systems have reached a critical transition point in their biophysical performance, social and environmental impacts, and energy patterns. The theoretical underpinnings of transitions towards sustainable futures have been studied from different approaches. The perspective of Social Metabolism (SM) studies how dynamic equilibriums of society-nature interactions arise in complex agroecosystems characterized by specific metabolic profiles that set their capabilities and limits. Changes between these regimes are understood as sociometabolic Transitions (SMT).This article offers a quantitative and qualitative review of how these SM and SMTs have been studied in Latin America so far, pointing out: i) the main conceptual and methodological approaches used, ii) the geographical scales of analysis, and iii) the main periods studied in the literature review. After identifying the different ways to account for the SMTs in LA, it discusses the prevailing SM narratives on the region's economic development. We found a scarce effort in carrying out multi-scalar studies linking national data with local case studies and a need to spread and adopt innovative SM methodologies and indicators to carry out more complex and comprehensive research on how inequality has framed the LA's agricultural paths and set their prospects.

1. Introduction: global environmental change and the sustainability role of agricultural systems

It is increasingly and widely recognized that our current social metabolism is unsustainable. During the upcoming decades, the global energy and materials demand is likely to grow by a factor of 2 to 3 (Krausmann et al., 2008), increasing the trespassing of several Earth system's limits and aggravating the current environmental crisis (Steffen et al., 2015). As never before, a global consensus calls for the urgent need to transform many nature-society relationships and to start a transition towards more sustainable social metabolisms.

One essential dimension of our social metabolism, both historically and at present, relies on the agricultural systems, which are complex socioecological systems co-regulated by socioeconomic and ecological processes (Haberl et al., 2011). Agriculture has been the basis of subsistence for our societies, providing us with food, raw materials, and energy for millennia. However, current agricultural systems have reached a critical transition point in their performance, environmental impacts (Tilman et al., 2002), and energy patterns (Gingrich and Krausmann, 2018). Nonetheless, the current global extension of agricultural land is predicted to double in the next 30 years to satisfy population demands (Tilman et al., 2001, 2002). This scenario is primarily projected for Global South regions that supposedly offer a surplus of agricultural land, suitable climatic and soil conditions, and an abundant labor force (Smeets et al., 2007).

The theoretical underpinnings of transitions towards sustainable futures have been studied from different approaches (Fischer-kowalski and Rotmans, 2009; Görg et al., 2017; Lachman, 2013, p. 269). Krausmann et al. (2008) define the dynamic equilibriums of society-nature interaction in complex systems as *sociometabolic regimes,* characterized by specific *metabolic profiles* that set their capabilities and limits. The changes in regimes are then understood as *sociometabolic Transitions* (hereto SMT) (Fischer-kowalski and Rotmans, 2009; Fischer-Kowalski and Haberl, 2007). This approach has been fundamental to understand long-term transitions (i.e., from hunter-gatherers to agrarian and to industrial regimes), offering a global systemic perspective backed by the robust conceptual framework of social metabolism (hereto SM) (González de Molina and Toledo, 2014) and different methodological

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tools and indicators (Fischer-Kowalski and Haberl, 2007). The study of SMT allowed us to understand, with great detail and from a sustainability perspective, the different historical SM paths that led some nations throughout the nineteenth century to an industrialized metabolic regime (Cunfer and Krausmann, 2015; Guzmán-Casado et al., 2018a, 2018b; Krausmann and Fischer-Kowalski, 2013).

To date, only a small group of societies belonging to highly industrialized countries has fully overcome the last SMT. Furthermore, many of these nations currently intend to transition towards more sustainable, post-industrial metabolic regimes (Haberl et al., 2019). Conversely, nearly two-thirds of the world's population- corresponding to Global South regions, are still under agrarian regimes or somewhere in the middle from agrarian and industrial ones. These nations are also at a crossroads between economic development and sustainability, facing the challenges of sourcing Northern economies with agri-food, oil, and mineral exports while struggling to reduce poverty and inequality, promote social inclusion, natural ecosystem protection, and fight climate change.

For instance, in Latin America (LA), the agricultural sector grows at an average of 2.7% per year. It contributes on average to 4.7% of the region's GDP, a figure partly attributed to an increase in agri-business developments (OECD/FAO 2019) at the expense of many subsistence-oriented and often agroecological peasant-farming units. This trend is expected to continue as, under a conventional economic view, the region must remain a significant source of agri-food commodities; a goal only achievable by raising production through intensive agro-industrial management many times imposed through land grabbing over agricultural land considered "underused" (Borras et al., 2012). Under this scenario, the future of LA is torn between *developmentalist* and sustainable agroecology paths (Altieri and Toledo, 2011). Finding feasible and desirable ways of sustainably advancing from the current conflictive realities of LA's agri-food systems is imperative.

Despite this scenario, there has been a scant effort to understand SMTs through the global North-South divide and the current SM patterns that establish both the constraints and the opportunities for any possible future transition in LA. We consider that the socio-metabolic approach is essential to understand these realities. However, the current tools and elements of this methodological and conceptual framework must be adapted and further developed to understand and navigate the current socio-ecological crisis in LA.

1.1. Goals and research questions

This article aims to review the existing SM studies of LA, focusing on agrarian metabolism, and to discuss their contributions to understanding and overcoming current LA's sustainability issues. Based on this revision, the article aims to respond to the following questions:

How has SM been studied in LA, and what can it tell us about Latin America's SMT towards industrialization? What are some remaining knowledge gaps and leading topics to be addressed by forthcoming research? And finally, how can this knowledge help address and overcome the current sustainability crisis of the region?

To do so, first, the article presents a brief introduction with the seminal work in SM and SMT, which have guided long-term sustainability studies around the world. Secondly, we define the methodology used to select and review the existing literature. Then, we present the results. Finally, we discuss these narratives and their contribution to the current reality of LA's rural world to spawn an interdisciplinary discussion over possible alternatives to address the current socioecological challenges in the region.

1.2. Seminal studies on social metabolism and sociometabolic transitions

1.2.1. Social metabolism

Over the past years, several comprehensive efforts have been made to synthesize the advancements in the use of SM both conceptually and methodologically (Gabriel et al., 2020; Gerber and Scheidel, 2018; Infante-Amate et al., 2017), and its usefulness for analyzing current global sustainability issues (Haberl et al., 2019). In-depth revisions and analyses for the agrarian dimension of SM have been carried out by Guzmán-Casado et al. (2018a, 2018b).

SM can be defined as the way in which human societies organize the exchanges of energy and materials with their natural environment to reverse the entropic process they are subject to (Fischer-Kowalski, 1998; González de Molina and Toledo, 2014). This framework presents a new perspective on humans' relationships with their biophysical environment by studying how the energy, materials, and information carried by societies interact with natural processes and change original ecosystems into cultural landscapes (Tello et al., 2006). Accounting for these interactions provides valuable information to assess a society's environmental sustainability (González de Molina and Toledo, 2014; González de Molina et al., 2012; Haberl et al., 2019).

There are two main conceptual and methodological approaches to SM. The most widely used is the Material and Energy Flow Accounting (MEFA), developed by the Sustainable Europe Research Institute (SERI), the Wuppertal Institute, and the Institute of Social Ecology in Vienna (SEC). MEFA is a stock-flow approach designed to analyze the biophysical trajectories of economies and societies today and throughout history (Fischer-Kowalski and Haberl, 2007; Krausmann et al., 2009). By accounting for the biophysical relationships between territories, MEFA can also describe how resources are appropriated, transformed, and consumed by societies (Haberl et al., 2007).

Mario Giampietro developed the second approach at the Institute of Environmental Science and Technology (ICTA). This approach is based on Goergescu-Roegen's (1971) reproductive, Fund-Flow model. It considers SM as an integrated set of functions expressed by a complex self-organizing system "capable of gathering energy and material inputs, and dumping wastes into the environment to reproduce itself according to the information stored in the system" (Giampietro et al., 2014, p. 24). Arguing that systems cannot be understood without looking at their multiple spatial and temporal scales, Giampietro et al. developed the Multiscale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) to study the nexuses among the different societal and ecological metabolic processes at different dimensions and scales (Giampietro et al., 2009).

1.2.1.1. Agrarian metabolism. Agricultural systems play a major role in the biophysical basis of our societies and their SM. Energy, materials, and information constantly enter exit and recirculate within agroecosystems, not only altering them but ultimately shaping the human-colonized territory (Font et al., 2020; González de Molina and Toledo, 2011; Guzmán-Casado et al., 2018a). The study of agroecological processes is the focus of Agrarian Metabolism (AM). Its study is based on complimentary SM methods, such as carbon balances and greenhouse gas emissions (Aguilera et al., 2018; Aguilera et al., 2019a, b; Billen et al., 2021), soil nutrient and water balances at an agroecosystem level (Cunfer and Krausmann, 2009; Garcia-Ruiz et al., 2012; Tello et al., 2012; Vila-Traver et al., 2021), and MEFA energy analyses (i.e., multi-EROI) at local, regional, and national scales (Guzmán-Casado et al., 2018a, 2018b; Tello et al., 2015, 2016).

The exploration of energy flows within agroecosystems has allowed tracking energy efficiency across SMTs in various industrialized nations (Galán et al., 2016; Gingrich et al., 2018a, 2018b; Gingrich and Krausmann, 2018; González de Molina et al., 2020; Guzmán-Casado et al., 2018b; Soto et al., 2016; Tello et al., 2016). These elaborations have been linked to landscape ecology analyses to evaluate territorial sustainability from an agroecology landscape perspective (Marull et al., 2016a, 2016b; Marull et al., 2018, 2019).

A crucial contribution of AM has been the agroecological and historical approach to study long-term agroecosystem dynamics (González de Molina et al., 2020; Guzmán-Casado et al., 2018a, 2018b; Guzmán-

Casado and González de Molina, 2015). Also adopting a fund-flow reproductive standpoint (Georgescu-Roegen, 1971), this approach undertakes questions related to the evolution and sustainability of agriculture since the beginning of the 19th century, mainly in Austria, Spain, France, the United States, and Canada (Cunfer et al., 2018; Gingrich et al., 2018c; Gingrich and Krausmann, 2018; González de Molina et al., 2020; Guzmán-Casado et al., 2018a, 2018b; Harchaoui and Chatzimpiros, 2019; MacFadyen and Watson, 2018; Parcerisas and Dupras, 2018; Soto et al., 2016). Combining energy and soil nutrient balances, it has been possible to understand the sustainability implications of SM changes on agrarian systems in the long run (González de Molina et al., 2012; Díez et al., 2018a; Garrabou Segura and González de Molina, 2010; Güldner, 2020; Guzmán-Casado et al., 2018b; Hercher-Pasteur et al., 2020; Llinàs et al., 2021; Marco et al., 2018; Padró et al., 2017).

1.2.2. Sociometabolic transitions

SMTs facilitate a clearer understanding of society's metabolic regimes' structural and functional transformations and their socio-ecological implications (Fischer-kowalski and Rotmans, 2009; Krausmann et al., 2016). They do it by identifying how societies transformed the land matrix used for their sustenance and informing the ruling actors and driving forces of these material and immaterial changes (González de Molina et al., 2020, p. 16; González de Molina and Toledo, 2014; Lachman, 2013, p. 274; Tello et al., 2017). The SMT triggered by the industrial revolution has been studied in biophysical terms to carry out analyses focused on local, regional, and national scales and the international interactions derived from trade flows to evaluate its implications at the global scale (Krausmann et al., 2008). The study of SMT is based on the society's material and energy bases and characterization of population densities, land use patterns, and specific features of the labor force (Fischer-Kowalski and Haberl, 2007; Schandl and Turner, 2009). Finally, this approach has been related to the literature on Food Regimes useful for tackling current world sustainability challenges. (Krausmann and Langthaler, 2019; McMichael, 2014),

2. Methodology

2.1. Literature review protocol

A systematic search of the literature was carried out to identify articles that deal with SM and SMT in LA. Searches in the scientific literature were performed using Web of Science and Google Scholar with the following sets of keywords to ensure the inclusion of studies dealing with at least three of the following topics: (1) Social Metabolism (e.g., soci* metabolic*); (2) Metabolic transitions (e.g., metabo1ic or socio-ecological transition); (3) Metabolic assessment (e.g., MEFA, MFA, MuSIASEM, Biophysical flows); (4) Latin America (e.g., Latin America, Global South, Developing countries), (5) Agrarian processes (e.g., agrarian metabolism, agroecosystem). Results of the search cover the period from 1980 to 2020. Citations ($N = 80$) were extracted and compiled on a citation database. Publication's abstract, keywords and methodologies were reviewed case-by-case to assure they were actually referring to SM and did not only allude to it, excluding off-topic articles. Additional relevant publications referenced on relevant articles that did not appear in the initial review were included. A total of 66 publications strictly referring to SM in LA remained.

An initial categorization was made according to i) the region and countries where each case study was developed or analyzed; ii) the type of research or article (i.e., single or many quantitative and empirical case studies, qualitative, discursive/theoretical); iii) the scale of data and analysis (i.e., product, farm, local, national or regional scale); iv) the level of the study (i.e., global, regional, national, local, agroecosystem or general); v) theoretical and methodological SM approach, as well as other complementary methodological tools, used. A summary of the query parameters applied in the analysis is presented in Table 1.

Other additional information, such as the principal author's association, language, time window analysis, data sources, and relevant analytical themes (i.e., Rural metabolism, Agrarian metabolism, Water metabolism, Social metabolism, Agroecology, Agrarian transitions, LULCC, Immaterial, Land use conflicts) were also recorded for complementary analysis when needed.

Table 1
Summary of query parameters used to review the literature on social metabolism in LA.

Category	Category name	Description	Examples
1	Region	Region and countries studied	Latin América, Europe, global or meta-analysis.
2	Type of article	Type of research documented	Quantitative empirical, qualitative, discursive/ theoretical single or comparative case studies.
3	Scale of data	The scale of the data used for the analysis	Product, farm, local, national, or regional scale
4	Level of analysis	The level at which the analysis was done	Farm/agroecosystem, local, national, regional, global or general.
5	Methodological approach	Main SM methodology used, as well as other complementary methodological tools used.	Main: Material and Energy Flow Analysis (MEFA), Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM), Input-output analysis (IOA). Complementary: HANPP, Socioecological Analysis, EROI, Soil Nutrient flows.

3. Results

We present the results in two sections. First, a quantitative overview of the studies reveals the extent and scope to which SM has been studied in LA. Specifically, it identifies the main conceptual and methodological approaches used and the geographical scales of analysis. Then, we present the specific contributions of SM literature to the understanding of SMT in LA, identifying the main periods proposed in the literature review.

3.1. Approaches to the study of social metabolism in Latin America

In general, most metabolic studies have focused on MEFA at the regional and country-level, offering a systemic perspective of the economy-environment relationships based on aggregated national data (Fischer-kowalski and Amann, 2001; Giljum and Eisenmenger, 2004). For Latin America, MEFA was also the most frequently used tool (47% of the time, $n = 27$), with assessments at local ($n = 2$), national ($n = 11$), and regional ($n = 11$) levels. By the submission of this publication, there were published metabolic profiles of the economies of Argentina (Perez-Manrique et al., 2013), Perú (Silva-Macher, 2016), Ecuador (Russi et al., 2008; Vallejo, 2010), Colombia (Pérez-Rincón, 2006; Urrego-Mesa et al., 2018; Vallejo et al., 2011), Costa Rica (Infante-Amate and Picado, 2018), México (Gonzalez-Martinez and Schandl, 2008) and Chile (Giljum, 2004). These studies are frequently focused on the overall country's economy, and seven of them focused on the agricultural sector or local agrarian processes (Delgadillo-Vargas et al., 2016; Infante-Amate and Picado, 2018; Pengue, 2005; Pérez-Rincón, 2006; Urrego-Mesa et al., 2018).

Through MEFA indicators (e.g., Domestic Extraction, Domestic Material Consumption, Domestic Material Input, and Physical Trade

Balances), LA metabolic studies have evidenced the deterioration in trade terms between these economies and industrialized ones, as well as an increase in energy consumption (Perez-Manrique et al., 2013) and material use (Vallejo et al., 2011). In dialogue with political ecology studies, a trend in the reprimarization of the economies (Pérez-Rincón, 2006), and the role of resource extraction on the generation of a myriad of socio-environmental conflicts also became clear (Martínez-Alier, 2011; Martínez-Alier and Walter, 2016; Muradian et al., 2012; Pérez-Rincón et al., 2018; Scheidel et al., 2020). Most studies addressing the evolution of land biomass flow throughout the 20th century have been conducted mainly locally. Only two recent studies in LA have used MEFA to analyze biomass production and its role in the economy at large or agrarian sector (Infante-Amate et al., 2020; Urrego-Mesa, 2021).

The second group of studies (14% of this review) adopts MuSIASEM to quantify and characterize the SM of LA's various economic sectors and activities (Borzoni, 2011; Recalde and Ramos-Martín, 2011; Silva-Macher, 2016). MuSIASEM studies ($n = 8$) were mostly done for regional ($n = 5$) and national ($n = 3$) levels. National-scale studies employing MuSIASEM revealed the high energy consumption and unsustainable metabolic energy rates of Peru's mining sector (Silva-Macher, 2016) and Brazil's soybean biodiesel industry (Borzoni, 2011). Due to the complexity of data required to carry out this multiscale analysis, studies often refer to punctual years in time. Only one presents a mid-term approach evidencing the unsustainability of the metabolic pathway of Argentina (Recalde and Ramos-Martín, 2011). A handful of MuSIASEM studies focus on the evolution of the agricultural sector and its metabolic implications for the rural sector at household (Mingorría et al., 2014; Ravera et al., 2014) and community levels (Arizpe et al., 2014). Lastly, one comparative, multitemporal analysis (1980 and 2000) using MuSIASEM explored the economic development of Brazil, Venezuela, and Chile. Observing the exosomatic energy trajectories (Ramos-Martín et al., 2008) shows the close relationship between commodity and natural resource export-based economies and the not yet completed industrialization.

Finally, and although it is not strictly a SM methodology, but rather an adaptation of the Material Flows Accounting in conjunction with socioeconomic indicators, a set of works studying SM in LA follows Toledo's (2008) social-economic proposal of rural metabolisms. Based on biophysical and economic flows, these works focused on the determinants of nature's appropriation process, as the beginning of the metabolic relationship between humans and nature, identifying the different material, energy, and information flows at the local and community scales for specific historical periods. Although the temporal scales used are not enough to elucidate a metabolic transition, Toledo's school is widely represented in the sustainability studies of LA, despite being underrepresented in peer-reviewed, international journals databases.

3.2. Contributions of SM literature to the understanding of SMT in Latin America

The study of SMT offers a historical perspective on how societies have organized themselves using nature to satisfy their endosomatic and exosomatic material-energy needs. The transition towards industrialized metabolic regimes has implied the expansion and intensification of the SM (Krausmann et al., 2009). Some determining factors of the SMT from an organic to an industrial metabolic regime have been well-established by analyzing population density changes, land use patterns, technological advancements that improve resource use efficiency, and waste disposal.

For LA, only a few works in the existing literature specifically address the SM, and most do it by using MEFA at the country (Falconí and Vallejo, 2012a; Infante-Amate and Picado, 2018; Urrego-Mesa et al., 2018) and regional scales (Eisenmenger et al., 2007). These studies revealed an increase in the use of non-renewable energies to fuel industrial processes in LA. Only two exceptions adopt different secondary SM methodologies, such as soil nutrient balances and Human Appropriation of Net Primary Production (HANPP) (Delgadillo-Vargas et al., 2016; Marull et al., 2017).

Most studies encompass, at the most, a 40 years' time window for the analyzes, corresponding to the last half of the 20th century. Only four studies include data before the 1950s (Delgadillo-Vargas et al., 2016; Infante-Amate and Picado, 2018; Marull et al., 2017; Urrego-Mesa et al., 2018), and two of them specifically carried out long-term biophysical accountings (Infante-Amate and Picado, 2018; Urrego-Mesa, 2021; Urrego-Mesa et al., 2018). These studies characterize and relate the SMT of agrarian sectors to the sustainability of the coffee agroecosystems in Costa Rica (Infante-Amate and Picado, 2018; Montero et al., 2021a, 2021b) and deforestation trends in Colombia (Urrego-Mesa et al., 2018).

The most geographically comprehensive study (Falconí and Vallejo, 2012a, 2012b) analyses the SMT for the Andean region by using MEFA accounts to evaluate economic efficiency, distribution, and physical sustainability. They proposed that LA economies have made scarce diversification efforts, relying on the extractive sector, especially non-renewable sources, and identified an increase in GDP, a poverty reduction, social inequity, and environmental pressure as key determinants to promoting socioecological transitions.

According to Krausmann et al. (2008, 2009) several of the trends identified by MEFA studies for LA could be considered signals of a transition towards industrial metabolisms. However, our review shows that such trends (i.e., the increase in the production of fossil energy in the Andean region between 1970 and 2009 or the urbanized population and the relatively high level of energy consumption per capita of Argentina) have not been enough to change the productive matrix of LA. Furthermore, it has not allowed overcoming the problems associated with LA's insertion model in world markets since the economies still highly rely on biomass production and other primary exports. In other words, rather than developing a strong industrial sector, LA countries have deepened and expanded their extractive economies (Giljum and Eisenmenger, 2004; Infante-Amate et al., 2020; Perez-Manrique et al., 2013). In this sense, Krausmann's typology for analyzing sociometabolic transitions might be too general to fit the features and trends of many LA economies.

However, the following section summarizes three significant periods of main socio-metabolic changes in LA identified throughout the literature review. These periods and breakpoints have to be taken with caution as they are based only on a limited number of studies in some LA countries. Therefore, they must be considered functional working hypotheses to carry out more research to confirm, reject, or amend them.

3.2.1. Main periods of the SMT in LA: driving and hindering forces

3.2.1.1. Before 1950. During the first wave (1916–48), the LA agrarian systems exhibited the standard features of the traditional organic or mixed industrial-organic farm systems, which throughout the First Globalization (1870–1914) had combined export-led specialization in some commodities (e.g., coffee and sugar in tropical areas or grains and meat in temperate ones) with a widespread domestic production of staple food (Urrego-Mesa, 2021). During the interwar period, the first liberal globalization went into the crisis with dramatic periods of exports downturns and punctual food shortages that gave rise to a general trend towards new import substitution policies and state-led developmentalist paths.

The literature reviewed reports a first preindustrial phase in countries like Colombia, where regional agriculture changed (Delgadillo-Vargas et al., 2016; Marull et al., 2017) and national biomass flows (Urrego-Mesa et al., 2018) suggested the beginning of a possible SMT. These changes responded to international, national, and local driving forces, such as international experts' missions and alliances, such as the Chardon Mission in 1929, Lauchlin Currie in 1950, the Lilienthal mission in 1954, and even the interventions of the Rockefeller, Ford, and

Kellogg foundations (Delgadillo-Vargas and Valencia, 2020; Picado, 2012), and later the Alliance for Progress (1961–1970). Precisely, an explicit aim of the Alliance for Progress was to spread the Green Revolution across LA to promote agricultural economic growth as an alternative to prevent more egalitarian land distribution regimes (Picado, 2008). This strongly influenced the trajectory of LA from the 1950s to1980s.

3.2.1.2. 1950s to 1980s. A second stage in the SMT began with Raúl Prebisch's ECLAC mandate and the state-led implementation of the guidelines for industrialization. It meant a steady increase in fossil energy extraction in the Andean region and an overall rise in mineral ores and other material extraction for the studied LA economies (Falconí and Vallejo, 2012a, 2012b; Infante-Amate et al., 2020).

This second wave of agrarian industrialization also began after World War II. It spread during this period with the increase of fossil fuel-based inputs as the primary source of agricultural external energy inputs mainly applied in the export-led growth of old and new agri-food commodities. A relevant share of the staple food for domestic consumption remained produced by small family farms under partial or total organic management (Altieri and Toledo, 2011).

3.2.1.3. 1980s to 2000s. After the 1980s debt crisis of the Andean countries, new reprimarization policies that drifted away from the CELAC objectives were adopted under the new neoliberal turn of the Washington Consensus adopted by the LA elites, discouraging the development of the industrial sector and cooperation among developing nations, forcing them to refocus on what "they have been known to do best": produce commodities to export to the global market (Hall and Pérez, 2000; Pérez-Rincón, 2006).

In the case of Colombia, during this third wave (1986–2000), annual rates of growth of the energy content of External Inputs slowed mainly due to the little advance in mechanization, while the use of fertilizers and pesticides almost three–folded (Urrego-Mesa, 2021). Despite the growth of these land-saving inputs that drove land intensification, mainly in the export sector, the agricultural frontier kept its extensive advance due to the skyrocketing export growth kept up to the present (Urrego-Mesa, 2021). The increasing dependence of most LA countries on essential staple food imports already evidences the loss of food security and sovereignty (Infante-Amate et al., 2020) and substantial threats to ecological functioning and sustainability (LaRota-Aguilera and Marull, 2022forthcoming). Only in some cases, like Costa Rica, deforestation has been halted, and a forest transition began in the early 2000s (Montero et al., 2021c).

3.2.2. From sociometabolic literature to political ecology

The reviewed SM publications align with the LA structuralist school's thesis of unequal exchange and add biophysical flow accounting to the market power asymmetries in price formation and value-added distribution (Pérez-Rincón, 2006; Prebisch, 1950). The literature supports the notion that the condition of unequal exchange has led LA to fail to insert into the world economy from a perspective other than a raw material supplier, and therefore, transit towards different metabolic stages (Kay, 2010). This statement goes hand in hand with what Falconí and Vallejo (2012a, 2012b) named the *specialization trap*. While LA exports poorly-paid and low-skilled labor products (e.g., natural resources), it imports expensive high-skilled manufactured goods from the Global North. This condition leads to an ever-increasing quantity of exports needed to obtain the same amount of imported goods (Ramos-Martín et al., 2008). A clear example is presented for Argentina, which has tried several times to follow a path of staple theory –a successful model for countries like Canada— but has only increased its dependence on commodity exports (Perez-Manrique et al., 2013). SM studies have also highlighted the market disadvantages of the agricultural sector in LA, dropping product prices while maintaining a high demand for imported agricultural inputs, leaving countries with a growing external debt (Hall and Pérez, 2000; Dorninger and Eisenmenger, 2016; Eisenmenger et al., 2007; Infante-Amate et al., 2020).

4. Discussion

4.1. The hindering forces of the SMT in LA

In a globalized economy, where countries are immersed in the international trade system, the socioeconomic metabolism is affected by the use and exchange of energy and material coming from and going to other societies. Accordingly, several of these nations' economic growth and industrialization paths have been facilitated or limited by the natural resource endowment of their physical environment. In some cases, the evolution of domestic extraction has not been driven by internal population growth (as in many already industrialized countries) but by biomass and mining exports (Perez-Manrique et al., 2013). In this sense, SMTs in "developing" countries have not depended solely on internal processes but have been mainly influenced by the international economy (Eisenmenger et al., 2007; Fischer-Kowalski and Haberl, 2007, chap. 3–5).

Throughout this review, a clear link with unequal exchange literature emerged (Emmanuel, 1972). Political Ecology and Ecological Economics (SM) literature coincide that the new international division of labor has promoted LA specialization in producing food and raw materials. This condition has led to a path of ecologically unequal exchange among industrialized core regions and "developing" peripheral ones (Eisenmenger et al., 2007; Falconí and Vallejo, 2012a, 2012b; Hornborg, 1998; Hornborg and Martinez-Alier, 2016; Muradian and Martinez-Alier, 2001; Pérez-Rincón, 2006). Under this thesis, LA continues to be a supplier of raw material and cheap labor, promoting dependency and "underdevelopment" in the region. Behind these unfavorable market and trade conditions is the incapacity of Global South economies to accumulate a surplus that strengthens industry development, hindering the completion of an SMT to industrialization (Eisenmenger et al., 2007). Economic development, then, might be considered a positional good—i.e., to be enjoyed for some, precisely because others are excluded (Naredo Pérez and Valero Capilla, 1999).

Linking biophysical and monetary flows allowed to understand the inequality hindering a transition in LA from a socio-metabolic perspective. For the agricultural world, this unequal situation is reinforced by LA payments of external debt to foreign lenders since the 1980s, often directed to external agricultural input acquisition (Hall and Pérez, 2000). However, a purely monetary accounting of their global trade and pricing does not reflect the environmental and social costs they mean for LA. The exchange also involves the export of LA's goods (e.g., minerals, oil, and biomass with high exergy values) while 'bads' (e.g., mining environmental liabilities and depletion of soil nutrients) remain in its territories (Anguelovski and Martínez-Alier, 2014; Martínez-Alier, 2003; Martínez-Alier, 2009; Muradian and Martinez-Alier, 2001). The expansion of agroindustry and the energy-mining model aimed at the foreign markets produces a widening of commodity extraction frontiers towards new territories where smallholder peasants and indigenous communities live carrying out sustainable ways of farming. The agricultural industrialization and the development impacts on LA territories and communities are reported daily by social movements, activists, and scientists, to the extent that it is recognized as an "internal colonialism" (Acosta et al., 2011). These unsustainable extractive dynamics are driven by an ever-growing demand for cheap raw materials and energy carriers from the global economic growth, mainly from the North, leading to a depletion of natural resources and environmental degradation in some of the most biodiverse regions and ecosystems of the world (Borzoni, 2011; Silva-Macher, 2016).

Another hindering force of these SMTs, although not directly assessed throughout the reviewed SM studies, is the weight of socio-political factors. Land grabbing, unequal land distribution,

institutional biases and weaknesses, the concentration of the industrial and extractive activities by global North-based multinationals, the lack of political will, and the corruption that maintains these monopolies raise a barrier to the transition towards more sustainable metabolisms (Martínez-Alier and Walter, 2016; Scheidel et al., 2018; Veltmeyer, 2019). Market prices of goods and labor act as switches that convert biophysical flows (i.e., materials and energy carriers) into income. The prices are strongly determined by the previously established distribution of the funds (i.e., land and capital goods) that provide those flows. These monetary flows are converted back into other biophysical flows of different quantity and quality in final consumption baskets, leaving a monetary surplus concentrated in the hands of a small group of people (e.g., local elites or multinationals) who increase their capital accumulation and decide the allocation of new investments to accumulate more natural resources, technological capital goods and financial assets (Marco et al., 2020; Nawn, 2016). It is, therefore, clear that ecologically unequal exchange paths have gone hand in hand with high levels of internal inequality in LA nations and the role exerted by the local elites, many times watching over the interests of multinational companies, in preventing other more egalitarian development paths (Kay, 2009; Kay, 2002).

4.2. Challenges of the SM research to understand sustainable transitions in LA

4.2.1. Long-term data availability and integrative methodologies

This literature review evidenced that the information available to conduct long-term metabolic analyses in LA is still limited. It does not provide enough historical depth to study the industrial SMT. Hence, there is an urgent need for more empirical studies that will gradually help define the time window of the transition. MEFA and MuSIASEM approaches provide a dynamic and comparative view of the pressures associated with material extraction in LA economies, an insightful assessment of the current prevailing trends. Nonetheless, they have some limitations for LA yet. MEFA's conventional indicators may be similar for countries that reflect different economic structures and trade patterns (Perez-Manrique et al., 2013). This limitation suggests the need to include in the analysis the role of internal and international policies (agents of immaterial metabolism) on the different SM paths among LA countries (González de Molina and Toledo, 2014).

On the other hand, studies adopting the MuSIASEM approach have not contributed notably to SMT data in LA. They provide interesting background data on the agrarian changes of some countries through snapshots of their metabolic patterns and shed light on multiscalar accentuating factors and drivers of change. However, MuSIASEM's potential can also be a limitation, since multidimensional and multiscale data is often unavailable for LA despite being a comprehensive tool. Furthermore, it is not particularly suitable to analyze long-term processes, as the SMT does (Gabriel et al., 2020; Gerber and Scheidel, 2018).

In this regard, a less discussed but clear challenge of SM and sustainability studies in LA is the lack of robust, congruent, and long-term data, a product of a history of institutional weakness and scientific underfunding. In turn, most SM studies in LA have used national statistics taken from FAOSTAT, making it difficult to trace the SMT based on sub-national data. This constraint will undoubtedly require more fieldwork to collect empirical data on agroecosystem functioning at the local level. Future studies could also benefit from the methodological approaches adopted by the Agroecosystems History Laboratory in Sevilla and the Territory and Ecology Lab in Barcelona (Spain). Information on past landscapes' functioning can also be figured out by studying current agroecological practices and agroecosystems. This new body of research, not yet explored in LA, combines historiographic methodologies with agroecology, energy, and landscape ecology analyzes (i.e., HANPP, Land Cost of Agrarian Sustainability, Landscape Efficiency) (Cattaneo et al., 2018; Guzmán-Casado et al., 2011; Marull et al., 2019; Marull et al., 2018; Marull et al., 2016b). It can be of help to study SMT from a LA and Global South perspective.

Those integrative approaches could be especially relevant for Andean countries, where agriculture is still highly practiced by native indigenous, peasant, and afro-descendant communities. Studying the myriad of current agricultural practices in LA could contribute to rescue knowledge lost decades ago on the organization of agricultural landscapes. Furthermore, this knowledge can be linked to regional and national narratives on SMT, with potential contributions to a transition towards sustainability.

4.2.2. Integrating spatial scales and the agricultural dimension

LA's assessments of the SMT have failed to articulate the material outcomes (MEFA analyzes) with a comprehensive observation of historical transformations, the different scales and societal configurations, and the social ruling forces behind these changes. Regional (Infante-Amate et al., 2020) and national (Urrego-Mesa et al., 2018) studies provide relevant quantitative time-series evidence on the region's shift from one socioecological regime to another. However, these studies might miss crucial subnational and local profiles in transition at the base of many LA economies (Grünbühel et al., 2007, p. 139), as well as the micro-structures producing the social movements that challenge the prevailing extractivism dynamics and raise sustainability claims (Amann et al., 2002). Local and agroecosystem scales, as well as the agrarian dimension, are essential to consider because, although agriculture in LA has progressively undergone a conversion towards more intensive, market-dominated management systems (R. Grau and Aide, 2008), small-scale and low-intensity agriculture remains the most common production systems (Altieri and Toledo, 2011). Even in the SM literature, this bias reinforces the difficulties of having reliable subnational data from public statistics, deriving on a predominantly technocratic macroeconomic view obtained from large-scale, commercial agriculture sector data, and masking concurrent agrarian and rural realities in which small-scale farmers rely on sustainability-oriented agriculture for their livelihoods.

MEFA methodologies still have to be fully adjusted to tackle the multiscale specificities of agricultural processes and agroecosystems (Guzmán-Casado and González de Molina, 2017). The bioeconomic and agroecological accounting of biophysical balances of farm systems and the patterns and trends observed in their Energy Return on Investment (EROI) from a fund-flow reproductive viewpoint offer promising analytical tools to evaluate their sustainability paths either at the farm and local scales or at regional and national level (Cattaneo et al., 2018; Díez et al., 2018b; Galán et al., 2016; Guzmán-Casado et al., 2018b; Guzmán-Casado and González de Molina, 2015). Moreover, these material and energy balances of agroecosystems open the way to other landscape agroecology modeling carried out at different spatial dimensions, providing integrated analysis fundamental for land use planning and other policy-making processes (Padró et al., 2020; Padro et al., 2020).

The existing literature suggests that the extractive metabolism typical of LA countries will directly impact the landscapes and land-use transformations. This territorial imprint reflects the different stages of metabolic transitions that coexist and sometimes fight among them in different scales and places (Marull et al., 2017; Montero et al., 2021b). However, very few of the metabolic studies for LA are linked to the spatial landscape dimensions and specific geographic spaces. This “territorialized” metabolic analysis will be fundamental to understanding how the reorganization of spatial patterns in socioecological systems shapes ecosystems and cultural landscapes (Fischer-Kowalski and Haberl, 2007, chap. 5). For the agrarian dimension, this territorialization means studying the links between material, energy, and information flows at the farm, local, country, regional, and global scales and across them.

According to Guzmán-Casado and González de Molina (2017), the center of our agri-food systems' unsustainability issues lies in their

dependence on external inputs, and overcoming this dependence entails this closure of internal loops of complex agroecosystems that give rise to new integrated agroecology territories (Wezel et al., 2016). Sustainable agricultural systems imply that agroecosystem funds such as soil fertility, livestock, and laboring communities should self-reproduce and be maintained (Padró et al., 2019). It is at the landscape scale where the most essential biophysical and biogeochemical soil cycles can be closed, accomplishing the conditions to scale up sustainable agroecology territories seen as the most comprehensive and integrative representation of a society's metabolism. This condition is at the core of the scaling up agroecology strategy currently claimed worldwide for food sovereignty movements and climate change mitigation and adaptation policies (Altieri and Nicholls, 2012; Barrios et al., 2020).

The current threats on food security, food sovereignty, ecosystem services, soil fertility, and biodiversity across LA make it urgent to advance this research. To that aim, integrative, multidimensional, and multiscale studies are needed. They can highlight issues that the contemporary political debate typically hides, such as the environmental costs of neoextractive policies.

4.2.3. New narratives

The SM and SMT literature for LA remain too circumscribed to the interpretive approaches developed for the countries of the Global North (Fischer-Kowalski and Haberl, 2007; Krausmann et al., 2009; Krausmann et al., 2008; Schneider et al., 2010). This trend can be seen among the predominant MEFA literature produced by La authors prone to the structuralist approaches of the Prebish school. Therefore, we argue that an epistemological twist towards post-structuralist proposals is needed to foresee LA's future transitions and development paths (Acosta et al., 2011; Escobar, 2010; Escobar, 1992; Gudynas, 2013). As long as the region will continue to play a pivotal role in global food production and exports, there seems to be no chance to advance towards more sustainable and fair paths.

To the question of whether or not these SM analyses and narratives help understand Latin America's environmental history and current rural realities, we answer that SM approaches are a helpful tool. However, the emergent SM studies should ignite a much-needed discussion about the impacts of land use and land cover change driven by external inputs dependence (i.e., the growing imports of chemical fertilizers while the life of cropland soils continues to deteriorate due to the loss of organic matter). To that aim, material fund-flow analyses of agroecosystems are fundamental. They need to be connected with economic accounting approaches of different emerging from the South, such as post-extractivism (Gudynas, 2013) and agroecological approaches (Holt-Giménez and Altieri, 2013). This literature will help navigate claims and policies towards more pertinent and sustainable socioecological paths in the continent and, hopefully, fill the current knowledge gaps on addressing a widespread change of LA agricultural systems.

According to González de Molina and Toledo (2014, p. 316), the main weakness of transition theories is their lack of political or institutional dimension analyses. Without new institutional frameworks favoring and developing SMT, transitions towards fairer and more sustainable futures will never occur.

Far from being driven only by scientific or technological efficiency physiognomy, SMT and the society-nature relationship are intricate. These processes affect different dimensions and levels of society, from land ownership entitlement and distribution to social imaginaries and values in dispute (Martínez-Alier, 2009; Martínez-Alier, 2003; Martínez-Alier and Walter, 2016). It is, therefore, fundamental to study the role of local communities' resistance and Global Justice movements as levers for sustainable alternative paths. Moreover, policy debates on future sustainability roadmaps for LA must integrate these symbolic values in dispute (Anguelovski and Martínez-Alier, 2014; Gerber and Scheidel, 2018; Scheidel et al., 2020; Scheidel et al., 2018). There is an excellent opportunity to enrich the Political Ecology analyzes on ecologically distributive conflicts (Martínez-Alier and Walter, 2016; Pengue, 2005; Scheidel et al., 2020; Vallejo, 2010) with Ecological Economy methodologies, such as SM. For instance, the cultural resistance of peasant and indigenous communities to extractivism is rooted in their growing agroecological practices, which are uprising across the LA continent as a counterweight to the deleterious effects of agricultural industrialization for both local communities and the environment (Altieri and Toledo, 2011). However, many of these local narratives are undermined by policy-makers, given the "lack" of rigorous scientific data supporting these claims. SM methodologies have great potential to provide quantitative assessments of the social and environmental externalities of LA's agri-food, mining, and energy sectors.

To keep uncritically projecting a future for LA following the unique path of rural and urban industrialization supposes an obsolete notion of development for the 21st century. This developmentalist straitjacket perpetuates the unequal power relations across the South-North economic divide and within Southern LA nations. It is, therefore, crucial to search for alternative transition pathways for a LA rural world that stays at a crossroads between the everyday resistance and claims of a myriad of smallholder peasant families and communities in agroecology landscapes increasingly grabbed by agribusiness and mining corporations that foster unsustainable and unfair paths set in motion by neoliberal economic and social policies from the last decades of the 20th century onwards (Brannstrom, 2009; Liverman and Vilas, 2006).

Some inevitable questions emerge from this analysis: Do these results change the prevailing narratives on the region's economic development? If so, what can SM studies tell us about the role played by the LA's external dependencies, the attitudes of rural elites and national and regional governments, and the current resistances of small peasants, indigenous communities, and social movements?

4.2.4. A final note on characterizing the unequal exchange

There is still a long way to research the unequal socioecological exchanges from a socio-metabolic, socioeconomic, and gender-integrated approach. To date, the debate on unequal exchanges has been approached almost exclusively from a global perspective focused on international trade flows, physical trade balances, and embedded labor and land. However, power asymmetries in self-regulated markets (Polanyi, 1944) and unequal social and ecological exchanges have been omnipresent also within nations, regions, and local communities (Bayliss-Smith, 1982). Furthermore, they are often closely related to other exploitative relationships, such as gender inequality, if not based upon them (Mies, 1986; Picchio, 2003; Picchio, 1992). So far, there have been only a handful of attempts to apply sociometabolic approaches to study in an integrated way all these inequalities and exploitative social relations on these other spatial and temporal scales (Gizicki-Neundlinger et al., 2017; Gizicki-Neundlinger and Güldner, 2017; Grünbühel and Schandl, 2005; Güldner and Krausmann, 2017; Padró et al., 2019; Scheidel, 2013).

Therefore, beyond accumulating empirical data on the persistence of LA new-extractivism based on socially and ecologically unequal exchanges with other parts of the world, more research and evidence is needed to bring to light the multiscale linkages between external and internal inequalities, their multifaceted character, and their joint operation using better socioecological approaches and methods that help resolve the current open debates on the subject (Dorninger and Hornborg, 2015). In a region of the world with the highest inequality figures, the analysis of societal unfairness from a sociometabolic perspective has great potential to connect with an extensive literature on agrarian class structures, and food regimes developed long ago by LA scholars (Kay, 2015; Kay, 2002; Kay, 1991). The SM study of the social inequality fabric can help provide new answers to the key questions posed by Henrry Bernstein (2010) on the long-term dynamics of agrarian change: Who owns what? Who does what? Who gets what? What do they do with it? These inquiries open an avenue of research for the theory of Ecological Economics and Political Ecology to study the interlinked and

multiscalar systemic character of all sorts of inequalities as exploitative relations among humans (Gerber and Scheidel, 2018).

5. Conclusions

This article reviews the literature on SM and SMT in Latin America. It confirms the importance of these Ecological Economics perspectives and methodologies to understand its past and present rural and agricultural realities. They are powerful analytical tools to provide new perspectives on the biophysical and socioecological foundations on which the national economies of LA have mainly been built with a highly unequal distribution of land and all sorts of resources.

However, these SM approaches have been developed mainly from the Global North perspective, which involves methodological and conceptual biases. Studying SM and SMT in Latin America requires discussing assumptions from different disciplines, human experiences, and worldviews concerning nature and society-nature interactions.

Developing a LA approach to SM and SMTs is a fundamental scientific task to address the key question of how to start a new transition towards more sustainable and fair societies in the region. This task requires developing new research that includes the different scales that make up the agricultural metabolism (i.e., from farm units to local landscapes, from provincial areas to national level, and from the entire LA region to the global economy), bringing to light all the multidimensional flows and nexuses interconnecting them (i.e., energy, biomass, ores, land, worktime, income, financial debts) in order to understand better the sociometabolic patterns and trends of this region and their unsustainability paths, as well as the possible alternatives to face the current socioecological crisis in the planet. This will help advance an agroecology transition towards agroecosystems and rural communities capable of self-reproduce themselves while preserving biodiversity and maintaining all ecosystem services (pollination, pest and disease control, clean water, and fertile soil, among others).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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