



Surveys

Long-term trends in resource consumption in Latin America: Integrating the MEFA and STIRPAT approaches

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ABSTRACT

This study investigates long-term trends and determinants of material consumption in Latin America, a region known for its rich natural resources and current environmental challenges. Using Material and Energy Flow Accounting (MEFA) methodology, the research analyzes Domestic Material Consumption (DMC) and Material Footprint (MF) across 17 Latin American countries from 1970 to 2019. An extended STIRPAT model evaluates the impact of macroeconomic, social, technological, environmental, and political factors on these indicators. The study distinguishes between direct and indirect material flows. The findings indicate that economic development alone cannot fully account for the increasing environmental pressure. Specifically, DMC per capita is more closely linked to raw material consumption compared to MF per capita. The research underscores an incomplete transition to industrialized agriculture, an increase in the importance of metallic and non-metallic minerals due to their growing extraction and consumption, and highlights the impact of social factors, such as life expectancy and human capital, on material consumption patterns. Additionally, technological advancements and the institutional context may also exacerbate environmental pressure. The study also reveals variations across different material categories, including biomass, fossil fuels, metallic minerals, and non-metallic minerals.

1. Introduction

The rapid escalation of global environmental crisis and its consequences (climate change, atmosphere pollution, biodiversity loss, biochemical cycle breakdown) seem closely linked to the global extraction and consumption of resources (IEA, 2021; IPCC, 2023; Rockström et al., 2023; UNEP, 2020). Extraction rates have surged fourfold over the last forty years, underscoring a persistent biophysical challenge exacerbated by the consumption and utilization of materials. With the highest global extractive percentage of 11 % in 2019, Latin America underscores the urgent need to address resource extraction issues (UNEP, 2020). Historically renowned as a “mine” of natural resources (Infante-Amate et al., 2022; Schaffartzik et al., 2014), the region was also perceived as a “virgin paradise” of natural wealth during the 19th and 20th centuries (Bértola and Ocampo, 2010). A number of

historical events have marked the consecutive increases in internal and external biophysical requirements for natural resources. This is the case of the two great world wars, the implementation of state-led industrialization (1930–1970), the capitalism’s golden age (1945–1973), the debt crisis (1980–1989), the agro-export boom and the commodities super-cycle (1990–2012) or the entry of China into Latin American markets at the beginning of the 21st century (Santana Suárez, 2019). The internal biophysical growth in Latin America can be attributed to several factors. Firstly, the imposition of trade barriers during the world wars and the crisis of 1930s made it difficult to import manufactured goods, leading to a shift towards domestic production. Secondly, the belief in the need for changes in production levels fostered industrialization through Import Substitution Industrialization (ISI). Lastly, improvements in social indicators, such as increased life expectancy, also played a role in driving this growth (Bértola and Ocampo, 2010; Helg,

Abbreviation: DE, Domestic Extraction; DMC, Domestic Material Consumption; ECLAC, Economic Commission for Latin America and Caribbean; EE, Ecological Elasticity; EP, Environmental Pressure; GDP, Gross Domestic Product; ISI, Import Substitution Industrialization; M, Imports; MEFA, Material and Energy Flow Accounting Method; MF, Material Footprint; PWT, Penn World Table; RME M, Raw Material Equivalents in Imports; RME X, Raw Material Equivalents in Exports; TFP, Total Factor Productivity; X, Exports.

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2023; Zuñiga, 2014). The external demand for biophysical flows was primarily driven by the heightened needs for raw materials, such as oil, agricultural products, and rubber, used as essential products during wartime conflicts. Additionally, the gradual liberalization of global trade and periods of rising raw material prices have further contributed to this growth (Helg, 2023; Infante-Amate et al., 2022). Projections indicate that Latin America is likely to face some of the most severe consequences of ecological crisis, given its historical and biophysical trajectory (Cárdenas and Orozco, 2022), amplifying the urgency of comprehending and addressing an escalating issue.

In recent decades, Material and Energy Flow Accounting (MEFA), a methodology pioneered by Fischer-Kowalski and Huttler (1999), has facilitated the identification and quantification of material flows utilized and extracted from the environment, elucidating their interactions with the economy (Krausmann et al., 2009). Building on this framework, the present study analyzes long-term trends in material consumption in Latin America and aims to identify the possible key factors driving the increase in environmental pressure, using Domestic Material Consumption (DMC)¹ and Material Footprint (MF)² as proxy indicators. Although Domestic Extraction (DE) could be another option to capture environmental pressures from resource extraction, we focus instead in these two indicators – DMC and MF – because they offer a broader perspective on the material basis of economies. DMC reflects the physical accumulation and consumption in national borders, and MF goes a step further by allocating global resource extraction to final consumption providing a consumption-based lens on environmental responsibility. These indicators are increasingly employed in environmental accounting and policy evaluation, particularly for their ability to incorporate trade-related pressures – something that DMC limited by its territorial scope cannot do (Giljum et al., 2015; Wiedmann et al., 2015). Moreover, from a social metabolism perspective, DMC and MF are better suited to reflect the physical scale and intensity of socioeconomic processes driving environmental burdens (Fischer-Kowalski and Weisz, 1999). Our study traces the material trajectories of 17 Latin American countries between 1970 and 2019 examining how historical, structural and regional dynamics have shaped resource use. We also disaggregate these trends by material categories (biomass, fossil fuels, metallic minerals, non-metallic minerals) to uncover differentiated patterns. To identify the determinants of DMC and MF, we employ an extended version of the STIRPAT model (York et al., 2003), using a panel data econometrics to explore the influence of macroeconomic, social, technological, environmental and political variables over time. Additionally, we acknowledge that DMC, MF and DE face inherent limitations. As Matthews et al. (2000) noted, the comparison of tonnes across material types does not directly translate into homogeneous environmental impacts, as different materials exert very different pressures. This is shared constraint of these metabolic indicators, and underline the need to complement material flow data with more impact-specific measures – such as land use, deforestation or greenhouse gas emissions – when assessing the full scope of environmental degradation.

The existing literature has concentrated on examining both indicators (DMC and MF), particularly in Europe (Bahers and Rosado, 2023; Cahen-Fourot and Magalhães, 2023; Eisenmenger et al., 2016; Kovanda and Weinzettel, 2013; Schoer et al., 2012). Additionally, global-level studies, such as that conducted by Frodyma et al. (2020) for 141 countries, have also addressed this topic. In Latin America, there has been interest in comparing both indicators, as seen in works such as those by CEPAL (2020) and Alonso-Fernández and Regueiro-Ferreira (2022). However, the predominant approach has been to use only one

indicator with MEFA approximation (Pérez-Rincón, 2023), as evidenced by studies as Crespo-Marín and Pérez-Rincón (2019), Eisenmenger et al. (2007), Giljum (2004), Gonzalez-Martinez and Schandl (2008), Perez Manrique et al. (2013), Russi et al. (2008), Schaffartzik et al. (2014), Vallejo (2010) and West and Schandl (2013). Several existing studies have utilized a combination of the IPAT or STIRPAT methodology with MEFA, incorporating either DMC or MF. For instance, Kassouri et al. (2021), Regueiro-Ferreira and Alonso-Fernández (2023), Wiedmann et al. (2015) and West and Schandl (2013) have explored similar methodologies. However, the first two studies do not focus on the Latin American continent; rather, they concentrate on selected countries within the region and do not provide material disaggregation. Conversely, while Regueiro-Ferreira and Alonso-Fernández (2023) offer a similar analysis, they focus on Europe. Furthermore, their study is primarily for fossil fuels, whereas our research addresses all material categories. Lastly, West and Schandl (2013) focus on the Latin American continent with a shorter sample period, no disaggregation. Therefore, our research addresses these gaps in the analysis of Latin America's sociometabolic profile and the factors shaping it, adopting a historical and quantitative perspective. Specifically, by integrating the MEFA and STIRPAT methodologies, our study offers a comparative examination of the evolution and drivers of two biophysical indicators, DMC and MF, across much of the continent. Thus, following the recommendations of LaRota-Aguilera et al. (2022), this study presents a comprehensive analysis of Latin American Social Metabolism, encompassing both aggregated and disaggregated group of materials (MFA4) examining the interconnections between material flows and various development factors, with the aim of understanding its socio-metabolic patterns.

The paper is structured as follows: In section 2, we outline the data and methodology utilized in this study. Section 3 discusses the primary findings, starting with an examination of material consumption trends and an exploration of the factors driving material consumption growth in Latin America. We then delve deeper into the heterogeneity among various material types, concretely on the DMC indicator. In Section 4 we discuss the main results, linking them to the empirical evidence and available literature on the subject. Finally, in Section 5 we present the conclusions, highlighting the main insights derived from the analysis.

2. Data and methodology

2.1. Data

We employ data on material consumption for 17 Latin American countries (Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Ecuador, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Paraguay, Peru, Uruguay and Venezuela). The selection of these 17 countries is based on a review of the sociometabolic literature focused on Latin America, identifying both countries already covered and those where research gaps remain. The Caribbean is excluded due to significant structural and sociometabolic differences with continental Latin America countries (CEPAL, 2020; West and Schandl, 2013). This study aims to contribute new empirical evidence and extent the scope of previous works focused on specific national or subregional cases, such as Crespo-Marín and Pérez-Rincón (2019), Eisenmenger et al. (2007), Giljum (2004), Gonzalez-Martinez and Schandl (2008), Perez Manrique et al. (2013), Russi et al. (2008), Vallejo (2010), Vallejo et al. (2011). Additionally, we use 13 different types of materials for DMC and 4 aggregates for MF (see MFA13 and MFA4 classifications in Table A1 of the Supplementary Material) over a period of 50 years, from 1970 to 2019. This time frame was deliberately chosen to ensure the identification of long-term structural drivers of material use while avoiding the distortions introduced by the COVID-19 pandemic and the subsequent economic shocks present in post-2019 data. This data comes from Global Material Flows Database (UNEP, 2022).

Firstly, we explain the trends, patterns and determinants of domestic material consumption per inhabitant (DMC pc) and material footprint

¹ Domestic Material consumption (DMC), termed as “apparent consumption”, encompasses materials directly consumed within a region.

² Material Footprint (MF), termed as “real consumption”, quantifies direct and indirect material usage flows associated with upstream production processes and international trade.

per capita (MF pc), focusing on their divergences. DMC refers to the actual reported materials directly used in an economy.³ It represents the apparent consumption in tonnes and is calculated from Domestic Extractions (DE), Exports (X) and Imports (M):

$$DMC = DE + M - X \quad (1)$$

The Material Footprint (MF) accounts the direct and indirect flows of extracted and traded materials throughout the global supply chain to meet final demands, representing the real consumption of an economy. The MF is calculated from the Domestic Extractions (DE) and the Exports and Imports of equivalent raw materials in direct and indirect material flows (RME X and RME M):

$$MF = DE + RME M - RME X \quad (2)$$

That is, the MF approach ensures that consumption is attributed to the final consumer, regardless of the country where the resource is extracted. We also use information for the factors that could explain the patterns of material consumption. The selection of these variables is based on a literature review that evaluates the productive activities linked to material extraction (MFA4 categories), trying to disentangle the factors affecting the production and consumption of these resources (see Table A2 in the Supplementary Material). We must take into account macroeconomic, social, technological and capital, environmental, political and international factors. Concretely, we use information on real gross domestic product (GDP) in absolute and per capita terms in 2017 constant dollars. This variable is taken from the Penn World Table (Feenstra et al., 2015). Regarding social variables, we use life expectancy and education indicators. The first one (LE) is an estimate of years of life at birth and comes from the The World Bank (2024). The education variable is the human capital index (HC), which reflects the ratio between wages earned and years of education of workers from Feenstra et al. (2015). As for technological change we use a proxy of technological progress, i.e., real total factor productivity (TFP) and the rate of capital depreciation (DELTA), both extracted from Feenstra et al. (2015). The environmental variables include the intensity of emissions, compiled as the ratio between CO2 emissions (Gigatonnes) and the GDP. The CO2 emissions data have been extracted from the Climate Watch database (World Resources Institute, 2022). Lastly, we consider political determinants; Political Freedom (PF) (Politics Rights and Civil Rights) and a globalization index (KOFGL). The first variable provides information on purely political aspects.⁴ Political Freedom is a variable calculated on the basis of the methodology used by Freedom House (2023) in the elaboration of its Freedom Status indicator. We obtain the variable “Political Freedom” as a quantitative measure ranging from 1 (representing the lowest degree of freedom) to 7 (representing the highest degree of freedom). This measure is derived from the average of two components: Civil Liberties and Political Rights. The data are taken from Freedom House (2023). Finally, the globalization index KOFGL, extracted from the ETH Zurich (Gygli et al., 2019), reflects the internationalisation and globalization of the countries on a political, economic and social level since 1970. This indicator is developed using trade, financial, cultural, the facts, and the legal political indicators.

In this way, we obtain a panel with 17 countries, a long period of time (50 years) and a disaggregation of 13 groups of materials, capturing the complexity of material extraction in Latin America. Table 2 shows

the main statistics for the selected variables. First, it reflects the characteristics of the Latin American region in general. A continent with a higher average level of DMC per capita than MF per capita (CEPAL, 2020), with a per capita income below than that of Western countries, lagging behind in social terms, very intensive in terms of CO2 emissions (Gt/\$) (Balza et al., 2024), with moderate international openness (CEPAL, 2020) and average political and civil rights, without achieving full democracies in many cases (Morlino, 2014; Valdebenito, 2022). Besides, the contrast between the minimum and maximum values of some variables, such as DMC pc or GDP pc, is striking, indicating that the selected sample of countries is very heterogeneous.

2.2. Methodology

The research is based on the Material and Energy Flow Accounting (MEFA) methodology (Fischer-Kowalski and Huttler, 1999) that allows to identify and quantify the flows of materials that are used and extracted from the environment and therefore their interactions with the economy (Krausmann et al., 2009). MEFA is currently being harmonized at the international level and is used by organizations such as ECLAC and Eurostat to produce socio-metabolic indicators and analyses. It offers an approach to the study of environmental pressure from a biophysical perspective (tonnes per capita).

In order to evaluate how political, social, technological or commercial determinants impact on the environment of Latin American economies, we use panel data analysis. Concretely, we study DMC pc and MF pc based on an extended version of the STIRPAT approach. York et al. (2003) proposed this stochastic model in order to circumvent the weaknesses of the IPAT equation proposed by Ehrlich and Holdren (1971), who explained environmental impacts (I) as a result of population size (P), affluence (A) and technological (T) changes. By incorporating natural logarithms, the STIRPAT model can be interpreted in terms of elasticities, which is referred to as “Ecological Elasticity” (EE) (York et al., 2003). This interpretation enables the calculation of EE for various factors impacting the environment in Latin America over the long term through regression analysis. This is a necessary step to provide basic insights into the relationships between variables and to pave the way for more advanced causal analysis. Without understanding these relationships and accounting for potential confounding factors in material consumption through regression, it would be difficult to draw robust conclusions about causality in future analysis.

Below we present the extended STIRPAT model that is used to assess the determinants of aggregate material consumption in Latin America. Departing from the explanatory variable of environmental pressure (EP) per capita, which can be whether DMC pc or MF pc, our complete specification would be as follows:

$$\begin{aligned} (EPpc_{it}) = & \beta_1 (GDPpc_{it}) + \beta_2 (GDPpc_{it})^2 + \beta_3 (LE_{it}) + \beta_4 (HC_{it}) + \beta_5 (TFP_{it}) \\ & + \beta_6 (DELTA_{it}) + \beta_7 (CO2/GDP_{it}) + \beta_8 (PF_{it}) + \beta_9 (KOFGL_{it}) \\ & + \delta_i + \gamma_t + u_{it} \end{aligned} \quad (3)$$

EP, measured alternatively by the MF per capita or DMC per capita, is expressed in natural logarithms. The explanatory variables include the logarithm of GDP per capita and its squared term.⁵ This enables us to account for the potentially non-linear relationship between economic development and environmental impact. This quadratic specification

³ The DMC indicator does not consider the so-called “hidden flows” (Carpintero and Naredo, 2004), but it can provide a complementary view to the one offered by the MF.

⁴ The relationship between political institutions and geography, defined as natural resources, has been the subject of considerable debate since the beginning of the 21st century (McArthur and Sachs, 2001). Institutions along with their policies and geography are closely linked and have been assumed to be key factors for economic growth (Aroca and Atienza, 2016; Grimm and Klasen, 2008; Perry and Schönerwald, 2012).

⁵ Despite the high degree of multicollinearity between GDP per capita and its squared, variables are kept due to their theoretical relevance for capturing its non-linear relationship. CO2 emissions per unit of GDP are also included to capture environmental efficiency as a distinct dimension from income. In this case, adjusted GVIF remains below common thresholds. Overall, adjusted GVIFs for all other covariates remain within acceptable limits, suggesting that multicollinearity is not a broad concern in the model.

allows us to test for the existence of turning points, where the trajectory of environmental degradation may shift as income levels rise beyond a certain threshold. This approach is consistent with both ecological economics and socio-economic metabolism, which emphasize the dynamic material and energy flows inherent in economic growth. As noted by York et al. (2003), the inclusion of polynomial terms, such as squared GDP, is theoretically appropriate when the underlying relationships are expected to be non-linear.

In addition to economic variables, we include several structural and institutional factors that may influence environmental impact. Specifically, we control for life expectancy (LE), the globalization index (KOFGL), the depreciation rate of physical capital (DELTA), and a measure of political freedom (PF), all included in levels. Furthermore, we incorporate the logarithm of the human capital index (HC), total factor productivity (TFP), and emissions intensity, to capture technological and efficiency-related dimensions of socio-economic metabolism. We include country fixed effects (δ_i) to control for unobserved, time-invariant heterogeneity across countries, and time fixed effects (γ_t) to account for common shocks or global trends that vary over time. The use of panel data allows us to exploit both the cross-sectional and temporal dimensions of our dataset, reducing omitted variable bias by capturing unobserved heterogeneity, as emphasized by Hsiao (2007). Based on the model's goodness of fit, information criteria (AIC and BIC), and the joint statistical significance of the fixed effects, we adopt eq. (3) as our preferred specification. This model structure allows us to better explain the variation in DMC per capita and MF per capita for the key materials analyzed in our sample, as discussed in Section 3.2.

To further ensure the robustness of our econometric inference, we conducted a series of diagnostic tests to examine the properties of the error structure in our panel data. Specifically, we tested for heteroskedasticity using the Breusch–Pagan test, for serial correlation using the Wooldridge test for autocorrelation in panel data, and for cross-sectional dependence using the Pesaran CD test. The results of all three tests indicated the presence of heteroskedasticity, first-order autocorrelation, and statistically significant cross-sectional dependence. In response to these violations of the classical assumptions, we estimated all models using Driscoll–Kraay standard errors, which are robust to heteroskedasticity, serial correlation, and cross-sectional dependence. This approach provides an estimation framework that accounts for the complex error structure observed in macro-panel datasets. The diagnostic test results are reported in Table A3 of the Supplementary Material.

3. Results

3.1. Determinants of aggregate material consumption in Latin America

Over the past 50 years, Latin America has experienced significant changes influenced by economic shocks, different economic policies, and global factors, shaping per capita material use. Fig. 1 shows the trends in DMC and MF per capita (right axis) alongside GDP per capita (left axis). DMC per capita grew by a factor of 1.8, from 9 t in 1970 to 16 t in 2019, while MF per capita increased by 1.65 times, from 8 to 13 t. During the same period, GDP per capita almost doubled. Notable growth occurred during 1970–1979 (commodity price increases), 1990–2008 (super-cycled commodities), and after the 2008 crisis. Thus, DMC and MF per capita are apparently associated with GDP per capita in recent decades, aligning with previous research (Alonso-Fernández and Regueiro-Ferreira, 2022; Crespo-Marín and Pérez-Rincón, 2019). Fig. 1 also shows that between 1970 and 2019, DMC per capita consistently exceeded MF per capita, with the gap widening during certain periods. Although material extraction appears linked to GDP per capita, other factors may explain material consumption patterns in Latin America. Table 3 presents estimation results that examine the association of these factors presented in Table 1 with DMC and MF per capita.

First, the impact of GDP per capita on material consumption is

negative, while the effect of squared GDP per capita is positive for both indicators, though significant only for DMC per capita (see Table 3). The observed signs for GDP suggest a nonlinear U-shaped relationship, where environmental pressure initially decreases with economic growth but increases beyond a certain threshold. The turning point is estimated to occur at a GDP level of \$975 in terms of DMC per capita, which is significantly lower than the region's average income of \$9000. This suggests that most countries in the sample have already passed this threshold, and economic growth now leads to increased environmental pressures. We also find a positive and significant impact of emissions intensity (Table 3).⁶ Inefficient and polluting production processes, could increase material demand. This is in line with the effect of technological development, measured by total factor productivity (TFP), which is linked to material extraction, with significance observed only for DMC per capita (Table 3).⁷ In addition to income, development encompasses social indicators such as education (measured by the Human Capital Index) and health (proxied by life expectancy). The findings in Table 3 suggest that as social welfare improves, material consumption tends to grow. Notably, the impact is more pronounced for DMC per capita. Likewise, Table 3 shows that rising globalization and improvements in political rights and civil liberties contribute to an increase in DMC per capita.

In summary, the findings presented in Table 3 offer a preliminary understanding of the relationship between material extraction and its explanatory factors. The results point towards a better fit for the DMC model, although it is not able to explain MF per inhabitant. This is not surprising, given that MF pc takes into account the direct and indirect flows attributed to a country's final consumption, while DMC pc better reflects the externalities resulting from material extraction in the country of origin. Having said that, rising incomes and improvements in social welfare have generally driven higher levels of material consumption in Latin America from 1970 to 2019. This trend has been further intensified by inefficient, environmentally damaging production practices, often linked to the slow adoption of clean and advanced technologies. Additionally, globalization and political freedom seem to increase pressures on the region's natural resources.

3.2. Divergences in materials types

Building on the previous results, we further investigate whether distinct patterns exist in the determinants of DMC per capita across the different material categories included in the sample—Biomass, Fossil Fuels, Metal Ores, and Non-Metallic Minerals—using the MFA4 classification presented in Table A1. In this section we only focus on material divergences for DMC, as the model is highly explanatory, with most of the determinants significant. Fig. 2 offers a descriptive assessment of the heterogeneity among these materials. At first glance, it underscores the predominance of Biomass in material consumption across Latin

⁶ To test the sensitivity of the results to alternative functional forms of GDP per capita, we estimated linear and cubic specifications for DMC and MF. The results, reported in Tables A4 and A5 of the Supplementary Material, confirm that the quadratic model offers the best balance of empirical fit and interpretability. For MF, the significance of the GDP per capita coefficient in the linear model suggests a monotonic relationship. For DMC, the quadratic specification improves explanatory power over the linear form and captures the expected nonlinearity. Although the cubic model yields a marginal improvement in adjusted R^2 and information criteria, it adds interpretive complexity with limited empirical gain. **Importantly, the findings for all other explanatory variables remain robust across model specifications.**

⁷ The implementation of technological change might not necessarily imply a reduction in pollution. In Latin America, natural resources are at the center of this debate and several authors highlight the relevant role of policies that manage the application of technology in extractive activities to achieve a decrease in environmental pressure (Cleary Gottlieb, 2023; Nathaniel et al., 2021).

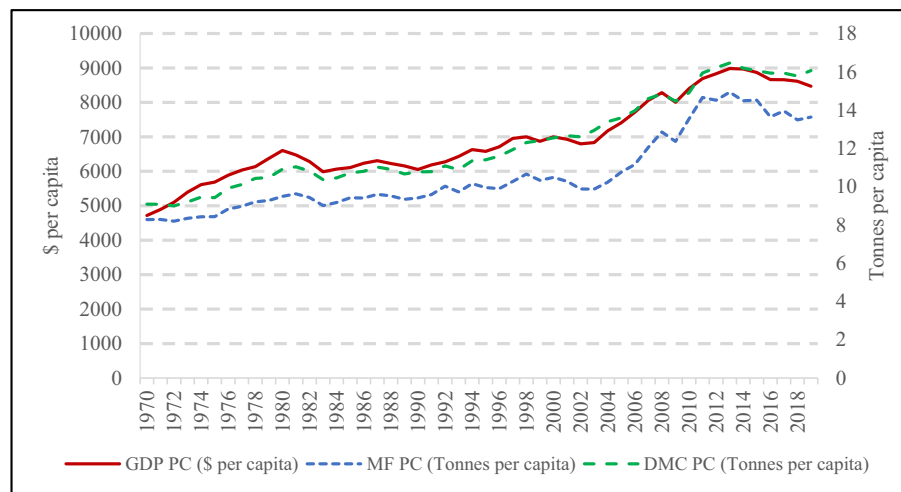


Fig. 1. Evolution of DMC, MF and GDP per capita in Latin America (1970–2019).
(Source: own elaboration based on PWT and UNEP)

Table 1
Sources and description of selected variables.

Type of Variable	Variable Name	Acronyms	Units	Source	Missing Values
Socio- metabolic	Domestic Material Consumption per capita	DMC pc	Tonnes per capita	UNEP and Material Flows	0 %
Socio- metabolic	Material Footprint per capita	MF pc	Tonnes per capita	UNEP and Material Flows	0 %
Macroeconomic	Gross Domestic Product per capita	GDP pc	Mil. of \$ per capita of 2017	PWT	0 %
Social	Life Expectancy	LE	Life years at birth	World Bank	0 %
Social	Human Capital Index	HC	Levels (Years of schooling in relation to income)	PWT	0 %
Technological and Capital	Proxy for Technical Progress	TFP	Levels (Mil. of \$ of 2017)	PWT	7.1 %
Technological and Capital	Capital Depreciation Rate	DELTA	Percentage	PWT	0 %
Environmental	CO2 Emissions Intensity	CO2/GDP	Gigatonnes per \$ of 2017	Own elaboration based on Climate Watch Data and PWT	0 %
Political	Political Freedom	PF	Levels (1–7)	Own elaboration based on Freedom House	4 %
International	Globalization Index	KOFGL	Levels	ETH Zurich KOF	0 %

Source: own elaboration.

Table 2
Summary statistics.

Variables	Minimum	Maximum	Mean	Median	N° Obs
DMC pc	3.602	53.003	11.656	8.893	850
MF pc	2.43	39.83	9.88	8.46	850
GDP pc	233.9	30,412.5	9241.8	7969.7	850
LE	46.6	80.35	68.54	70.02	850
HC	1.199	3.146	2.161	2.144	850
TFP	0.5671	31.747	11.224	10.331	790
DELTA	0.02142	0.07781	0.0426	0.03971	850
CO2/GDP	5.33E-05	1.65E-02	7.45E-04	1.62E-04	850
PF	1	6.5	3.088	3	850
KOFGL	30	77	51.53	51	850

Source: own elaboration.

America, followed by Non-Metallic Minerals. Both material categories exhibit similar trends. However, greater heterogeneity is observed in the patterns of Metal Ores and Fossil Fuels. In order to provide support for the inferences derived from Fig. 2, we extend the model by including material groups.

The biomass model replicates the results for nearly all baseline variables, with consistent signs and significance, except for the political freedom variable (Table 4). The results indicate a non-linear U-shaped relationship for biomass, with a turning point at approximately \$34,900

per capita. Since no Latin American country reached this threshold in 2019, all countries in the region remain on the declining segment of the curve. This pattern contrasts with the results for aggregate material consumption. Additionally, biomass consumption shows a positive relationship with social variables, particularly education, which exerts a more significant effect compared to the baseline. A similar trend is observed in TFP, where the impact on biomass consumption is substantially larger than that for aggregate material consumption. Technological development plays a crucial role in influencing biomass extraction in Latin America.

The findings also reveal a non-linear U-shaped relationship between economic growth and fossil fuel utilization, with a turning point at approximately \$9000 per capita. By 2019, most Latin American countries—such as Ecuador, Colombia, Argentina, Brazil, and Mexico—had surpassed this threshold and were positioned on the ascending segment of the curve. In contrast, countries like Bolivia and Venezuela remained on the descending segment. This variation in the development of fossil-fuel-linked sectors, particularly petroleum, underscores the existence of diverse economic growth trajectories within the region. Improvements in human capital and life expectancy strongly drive fossil fuel extraction, as it is the material group with the most pronounced impact. Specifically, in the case of fossil fuels, the depreciation of technological capital (delta) significantly reinforces fossil fuel extraction in the region. Conversely, greater openness to global markets and a higher intensity of

Table 3

Estimation results for aggregate DMC per capita and MF per capita.

	DMC per capita	MF per capita
Log GDPpc	−1.755*** (0.4083)	−0.0535 (0.4943)
Log GDPpc_sq	0.1275*** (0.0258)	0.0165 (0.0268)
LE	0.0403*** (0.0039)	−0.0014 (0.0043)
Log HC	0.9233*** (0.1748)	0.4119 (0.2993)
Log TFP	0.3792*** (0.0780)	0.1934 (0.1325)
DELTA	−1.448 (2.399)	−0.0427 (1.020)
Log CO2_GDP	0.0840*** (0.0304)	0.0974*** (0.0304)
PF	0.0157* (0.0091)	0.0271*** (0.0079)
KOFGL	0.0137*** (0.0034)	−0.0046* (0.0028)
Country fixed-effects	Yes	Yes
Time fixed-effects	Yes	Yes
Observations	760	760
R ² Adjusted	0.90168	0.91430
AIC	−577.70	−615.27
BIC	−244.10	−281.67

Driscoll-Kraay standard errors in parentheses.

Significance levels: *** 0.01, ** 0.05, * 0.1.

emissions relative to GDP appear to act as countervailing forces that reduce fossil fuel consumption.

For metal ores, two distinctive factors stand out. First, technological development exerts a strong influence on the extraction of metallic materials. Second, improvements in political freedom across the region have contributed significantly to increased metal extraction. Meanwhile, for non-metallic minerals, two key factors emerge as particularly impactful. Capital depreciation stimulates the consumption of these minerals, though to a lesser extent than for fossil fuels. Additionally, the intensity of emissions relative to GDP—a proxy for the pollution profile of production processes—places considerable pressure on non-metallic mineral consumption, producing the largest impact among all material

groups. Finally, as observed with fossil fuels, increasing global integration appears to help mitigate pressures on non-metallic minerals.

4. Discussion

Over the past 50 years, Latin America's material consumption has increased significantly, as Fig. 1 shows. Our findings emphasize the distinct patterns of material use, shaped by the region's resource specialization and uneven development trajectories. The analysis highlights several key determinants of material consumption. Factors such as economic growth, technological development and polluting production processes boost material demand. Social indicators are also positively associated with rising material consumption, while institutional and globalization effects reveal a mixed influence.

Economic growth and material consumption exhibit a non-linear U-shaped relationship (Table 3). The region's specialization in low value-added resource extraction helps explain why per capita income is a significant determinant of DMC per capita, whereas GDP per capita shows no significance for MF per capita. These results highlight the more immediate and territorially grounded nature of DMC and its close link to extractive activities, which includes trade directly, whereas MF captures both direct and indirect material flows embedded in international trade. In most Latin American countries, environmental pressures increase as income continues to grow, especially beyond the turning points identified in the quadratic models. Similar patterns have been identified in national studies on Peru (Moreno Moreno, 2018), Ecuador (Massa-Sánchez et al., 2020; Naula Pérez, 2019), and the region as a whole (Macas Segovia, 2023; Pinilla Rivera et al., 2018). The relationship between GDP and DMC is particularly strong for biomass and fossil fuels (Table 4), reflecting distinct structural characteristics of the region's economy.

In the case of biomass, the evidence suggests an emerging but incomplete agro-industrial transition in many countries. Firstly, Latin America continues to play a major role in exporting raw agricultural materials while importing manufactured goods with higher value-added components, contributing to an unequal ecological exchange between regions (Infante-Amate et al., 2022; Schaffartzik et al., 2014). This pattern is characteristic of non-industrialized economies that function primarily as suppliers of natural resources. Secondly, Martín-Retortillo

Table 4

Estimation results for DMC per capita across materials (MFA4).

	Baseline	Biomass	Fossil Fuels	Metal Ores	Non-Metallic Minerals
Log GDPpc	−1.755*** (0.4083)	−1.109*** (0.2644)	−8.434*** (2.722)	0.0481 (1.783)	1.275 (0.9314)
Log GDPpc_sq	0.1275*** (0.0258)	0.0530*** (0.0125)	0.4626*** (0.1520)	−0.0259 (0.1101)	−0.0289 (0.0498)
LE	0.0403*** (0.0039)	0.0138*** (0.0044)	0.1864*** (0.0373)	−0.0134 (0.0267)	0.0561*** (0.0071)
Log HC	0.9233*** (0.1748)	1.341*** (0.1873)	2.369** (1.027)	−1.235 (0.8543)	−0.4348 (0.6842)
Log TFP	0.3792*** (0.0780)	0.7957*** (0.0763)	1.032* (0.5492)	2.080*** (0.5781)	−0.0396 (0.3350)
DELTA	−1.448 (2.399)	−1.460** (0.7029)	42.00*** (10.70)	−7.616 (5.673)	7.385* (4.092)
Log CO2_GDP	0.0840*** (0.0304)	0.1094*** (0.0271)	−0.6757** (0.3191)	0.1224 (0.1656)	0.5349*** (0.1119)
PF	0.0157* (0.0091)	−0.0063 (0.0087)	0.0155 (0.0412)	0.0952** (0.0382)	0.0424** (0.0191)
KOFGL	0.0137*** (0.0034)	0.0126*** (0.0031)	−0.0691*** (0.0174)	0.0122 (0.0093)	−0.0154 (0.0101)
Country fixed-effects	Yes	Yes	Yes	Yes	Yes
Time fixed-effects	Yes	Yes	Yes	Yes	Yes
Observations	760	760	727	753	760
R ² Adjusted	0.90168	0.95670	0.78370	0.90694	0.75124
AIC	−577.70	−1214.0	1807.0	1323.4	671.85
BIC	−244.10	−880.39	2137.5	1656.3	1005.4

Driscoll-Kraay standard errors in parentheses.

Significance levels: *** 0.01, ** 0.05, * 0.1.

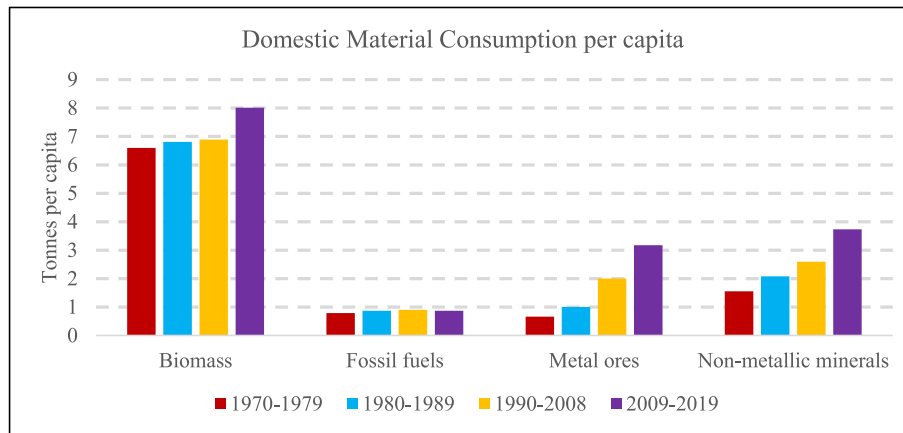


Fig. 2. Evolution of average DMC per capita by periods and groups of materials for Latin America (1970–2019). (Source: own elaboration based on UNEP)

et al. (2022) offer a complementary perspective that reinforces the U-shaped hypothesis by highlighting the crucial role of technology and capital in the biotics and agricultural sectors. Our results confirm that TFP could have a significant positive effect on biomass as Table 4 show. Macas Segovia (2023) note the high cost of acquiring advanced or clean technologies that limits their adoption in developing economies. CEPAL (2017) also emphasizes that structural change in these economies often involves incorporating technology into lower value-added sectors. Productivity improvements could also increase environmental pressures due to structural factors in Latin American agriculture, where family farms dominate. These small-scale farms often face limited access to technology and capital, potentially leading to less efficient resource use and higher material consumption (Martín-Retortillo et al., 2022). Nevertheless, these conditions have not spread uniformly across Latin American countries, resulting in uneven productivity growth and technological adoption throughout the region as a consequence of the contrast between small and large exploitations specialized in exporting biotic products (Elverdin et al., 2018).

For fossil fuels, the region presents a mixed model with signs of partial industrialization. Latin America is a global petroleum powerhouse in terms of resource extraction and reserves (García and Garcés, 2013). However, it has increasingly become a net importer of manufactured fossil fuel products (CEPAL, 2020), highlighting the gap between extraction and refining capacity in the fossil fuel sector—particularly in the petroleum industry. This pattern is reflected in our regression results, where capital depreciation shows a strong and positive effect on fossil fuel DMC (Table 4), pointing to infrastructure obsolescence as a key factor in increasing material demand. Nevertheless, the heterogeneous nature of the region complicates this generalization. While many countries face similar challenges, the production structures of major petroleum-producing nations vary considerably and encounter different issues related to capacity and industrial development (García and Garcés, 2013; Portillo Riascos, 2015; Serrani, 2013). Another critical issue is the preservation and renewal of large-scale infrastructure (Ffrench-Davis Muñoz and Vivanco, 2016). Countries like Argentina, Mexico, and Ecuador face pressing challenges in modernizing their facilities to maximize productive efficiency, a strategy already in progress in Brazil and Colombia (Oliva Camacho Flores, 2006; Portillo Riascos, 2015; Serrani, 2013). In contrast, the situation in Bolivia and Venezuela is more complex. Bolivia's limited infrastructure hampers its energy sector (Villegas Quiroga, 2004), while in Venezuela, declining revenues from fossil fuel activities have led to a drop in total factor productivity due to insufficient investment to offset depreciation (Hernández, 2006). Overall, fossil fuels have been essential for economic growth in many Latin American countries for decades, with the link between economic growth and environmental pressure closely tied

to the stock and maintenance of physical capital.

In the case of Metal Ores, extraction is primarily driven by technological development. This is in line with our empirical finding of a positive relationship between TFP and metal ore DMC (Table 4). The iron and steel sector, in which blast furnaces, historically coal-fired, are in the last decade adopting a process of replacement and switching to natural gas (Madias, 2013, 2020). This could support the positive influence of TFP on the metallic minerals consumption (Madias, 2013). In the same direction, a recent wave of technological advancements such as automation and digitalization has improved metal ores mining, mainly in medium and small mining (Robles et al., 2020). However, it should be noted that the technology levels of the biggest transnational companies are high and they have the latest innovations available (3D printing, 3D cartography, drones, digital twins, simulation models), albeit the sector remains under-technified in medium and small-sized companies with significant room for further progress (Tecnología Minera, 2023).

As we have seen in Table 4, the influence of emissions intensity relative to production on material consumption in Latin America is mixed, depending on the material type. This divergence is likely due to various factors, such as the region's gradual industrialization, the adoption of resource optimization techniques, recycling, the use of alternative energies, and decarbonization efforts. Most of the carbon emissions in the region stem from agriculture, deforestation, and land use changes (World Bank, 2022). For biomass, these practices, along with a lack of mechanization, impede progress towards more advanced models, which is reflected in the CO₂/GDP coefficient in the biomass regression (Table 4). Although efforts like climate-smart practices, conservation agriculture, the bio-economy, and green technologies are emerging, more state-led initiatives, such as promoting capital-intensive methods over land-intensive ones, are essential to accelerate mechanization and reduce emissions (Elverdin et al., 2018; Martín-Retortillo et al., 2022). For non-metallic minerals, the extraction of materials like gravel, sandstone, and phosphorus involves significant pollution (Del Río Gamero, 2018; UNEP, 2019). Our results confirm that emissions intensity has a positive and statistically significant effect on their DMC (Table 4) despite technological advancements that have been suggested for mitigation like reducing gravel consumption, using recycled materials or adjusting cement compositions. In the case of fossil fuels, decarbonization efforts are crucial, as supported by the negative impact of carbon intensity on DMC (Table 4). Coal combustion is being gradually replaced by natural gas (CEPAL, 2019a; Icaza-Alvarez et al., 2024; OCDE et al., 2021). Countries like Mexico, Peru, and Argentina are leading this shift, developing the natural gas sector through innovations such as electricity generation and transport via pipelines and liquefied natural gas shipping (Koop, 2022).

The dominance of primary goods and natural resource-based

manufacturing sectors in the region's economic structure—an economy which has grown considerably since the 1970s with improvements in human capital as well as in many other aspects as a result of economic growth—helps to explain the positive association between human capital and material consumption (Table 4) (Brito Gaona and Iglesias Vázquez, 2021; UNEP, 2020). There is no consensus in the literature, as Nathaniel et al. (2021) argue that human capital should mitigate environmental pressure (measured as CO₂ emissions), while increasing economic growth increases environmental pressure in biophysical terms (UNEP, 2020). Meanwhile, Blanco and Grier (2012) argue for agriculture that the effect between human capital accumulation and agricultural export specialization is negative, which neither confirms nor disagrees with our results as we focus on consumption. In parallel, the positive coefficient for life expectancy in Table 4 aligns with the improvements in this variable, which has converged with levels seen in North America, Europe, and Oceania (CEPAL, 2019b), present emerging policy challenges. Rising life expectancy may increase demand for biomass-based products to secure food sovereignty (Escobar, 2016; Evans, 2023), for fossil fuels to meet regional energy needs (CEPAL, 2023; IEA, 2023; Li et al., 2023) and for sandstone gravel and phosphorus, essential for fertilizer production and urban development (CEPAL, 2023; Kogan and Bondorevsky, 2016; Li et al., 2023).

Latin America's development trajectory has also been shaped by increasing integration into global markets (García-Herrero et al., 2014), which has placed significant environmental pressure, as evidenced by the positive coefficient for aggregate DMC and especially for biomass (Table 4). The region's international competitiveness is largely based on the production of goods with high raw material requirements, reinforcing its role as a supplier of primary commodities. This aligns with Alonso-Fernández and Regueiro-Ferreira (2022), who highlight how Latin American countries respond to trade imbalances by expanding the physical export of commodities during price spikes. This pattern is particularly pronounced for biomass, as the region's specialization in its production and export has driven an increase in biomass-related DMC (Martín-Retortillo et al., 2022; Nin-Pratt et al., 2015). In contrast, trade patterns in fossil fuels are heavily influenced by the dominance of Saudi Arabia, Russia, and Iran in global markets (Maugeri, 2007), which helps explain the negative association between fossil fuel DMC and the globalization index in the region (Table 4). Even though a high percentage of the extraction of these resources are consumed inside.

Finally, an increase in the Political Freedom variable, which reflects improvements in political rights and civil liberties, has been shown to intensify environmental pressure in most material groups (Table 4). This finding contradicts the argument presented by Sanders et al. (2019), who associate democratic progress throughout the 20th century with stricter regulations that, in some cases, have mitigated resource over-exploitation. However, in Latin America, the expansion of freedoms appears to have taken a different trajectory. This pattern may be linked to governments that, despite fostering greater liberties and public participation, have prioritized resource extraction as a growth strategy to enable subsequent income redistribution—an approach commonly referred to as neoextractivist policies. Furthermore, the increasing presence of large multinational corporations, facilitated by certain legislative developments (Núñez Domínguez et al., 2015), may have exacerbated environmental impacts compared to smaller producers, particularly in the mining sector (Brand et al., 2016; Burchardt and Dietz, 2014).

5. Conclusions

This paper applies the MEFA methodology to analyze long-term trends in material consumption in Latin America and to identify the key factors shaping the historical development of natural resource utilization. MEFA offers a robust framework for understanding the complex processes that influence material consumption patterns over time. Central to this study are two of MEFA's core indicators—DMC and

MF—which serve as proxies for environmental pressure. To examine the drivers of material consumption, we employed an extended STIRPAT model, estimated using panel data across 17 Latin American countries over the period 1970–2019. This modelling framework enabled us to assess the influence of macroeconomic, social, technological, environmental, and political factors that contribute to increased environmental pressures. By combining MEFA's physical accounting with an extended STIRPAT model, this study bridges the gap between descriptive material flow indicators and explanatory modelling, offering a novel approach to understanding the structural and dynamic drivers of material use in the global south. Our results demonstrate a significantly stronger correlation between these factors and DMC per capita, which motivated further analysis through the disaggregation of DMC per capita into four MFA material categories.

The findings reveal that rising incomes and improvements in social welfare have been primary drivers of material consumption in Latin America between 1970 and 2019. This trend has been exacerbated by inefficient and environmentally damaging production practices, often resulting from the slow adoption of cleaner and more advanced technologies. Globalization and institutional policies have also played a contributing, though secondary, role in intensifying pressures on the region's natural resources. A closer examination of DMC trends yields four key conclusions, underscoring the intricate relationship between economic development, policy decisions, and environmental sustainability in the region.

First, the region shows an incomplete agro-industrial transition, indicated by a U-shape relationship between GDP per capita, with the turning point below current income levels. This pattern is associated with biomass, suggesting that material intensity increases again as countries grow, consistent with Unequal Ecological Exchange hypothesis. Productivity gaps and limited access to cleaner and capital-intensive technologies, especially in small scale agriculture and biomass-intensive sectors, reinforce this trend.

Second, technological advancement and capital investment have notably impacted material consumption, particularly in fossil fuels and metal ores. Although some countries show signs of industrialization with rising DMC in these sectors, persistent inefficiencies, outdated infrastructure, and high capital depreciation contribute to increasing environmental pressures rather than mitigating them. The uneven industrial transformation across countries highlights the need for tailored policy approaches.

Third, the region's growing integration into global markets has consolidated its role as a net exporter of natural resources, with biomass being the most sensitive to globalization driven pressures. The effect of globalization is asymmetrical: while it amplifies biomass DMC due to export-oriented agricultural production, fossil fuels DMC shows a negative association with globalization, influenced by external competition and declining refining capacities. These patterns reflect Latin America's peripheral position in the international division of labour and highlight its ongoing dependence on resource-based sectors.

Fourth, institutional and political factors further complicate the material consumption landscape. Although the expansion of political rights and civil liberties is typically associated with stronger environmental regulation, our findings suggest that in Latin America these processes have often coincided with increasing material pressures. This paradox is particularly relevant in the context of neoextractivism development strategies, in which the expansion of extractive industries is justified as a source of fiscal revenue and social redistribution. Furthermore, legislative changes have facilitated the growing presence of large multinational corporations, particularly in the mining and fossil fuels sectors, reinforcing capital-intensive and resource-intensive development paths.

Overall, these findings point to a structural trajectory in which Latin America's economic development, technological change and institutional arrangements converge to reinforce material-intensive growth, rather than decouple economic activity from environmental pressure.

The region's continued reliance on primary exports, combined with underinvestment in sustainable infrastructure and innovation, poses significant challenges for long-term ecological sustainability. Addressing these challenges requires implementation of targeted, sector-specific environmental policies that promote cleaner production, enhance energy and resource efficiency, and support inclusive and sustainable industrial development. Governance frameworks must be strengthened to align institutional incentives with environmental goals, ensuring that increased political participation translates into more effective environmental protection. Given the complex and multi-scalar nature of material consumption drivers, regional cooperation and knowledge-sharing between countries will be essential to enhance policy outcomes and reduce ecological asymmetries. Finally, the study underscores the value of integrating biophysical indicators – such as DMC and MF- with disaggregated material categories and explanatory modelling approaches. Future research should further investigate these dimensions, establish causal relationships, and integrate trade dynamics into analyses to provide deeper insights into material consumption and environmental impacts, complementing the biophysical indicators and material differentiation examined in this study.

Declaration of generative AI in scientific writing

The authors declare the use of generative AI and AI-assisted technologies in the writing process to improve the readability and language of the manuscript.

CRediT authorship contribution statement

Javier Lozano-Morra: Writing – original draft, Visualization, Supervision, Software, Methodology, Investigation, Formal analysis. **Iñaki Iriarte-Goñi:** Writing – review & editing, Validation, Resources, Project administration, Funding acquisition. **Ana Serrano:** Writing – review & editing, Validation, Software, Methodology, Data curation, Conceptualization.

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Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolecon.2025.108801>.

Data availability

The data used in this survey are openly accessible and available online. They are referenced in the manuscript.

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Glossary

- MEFA:** Material and Energy Flow Accounting, is a methodology which has facilitated the identification and quantification of material flows utilized and extracted from the environment, elucidating their interactions with the economy.
- STIRPAT:** Stochastic model which explain environmental impacts (I) as a result of population size (P), affluence (A) and technological (T) changes. By incorporating natural logarithms, the STIRPAT model can be interpreted in terms of elasticities, which is referred to as “Ecological Elasticity” (EE). This interpretation enables the calculation of EE for various factors impacting the environment in Latin America over the long term through regression analysis.
- MF:** Sociometabolic indicator which represents the consumption patterns in physical terms of the population from the consumption and production perspective. This is the main difference with the DMC which only takes into account the output side. It is calculated as $MF = DE + (RME\ M - RME\ X)$. Where DE is Domestic Extraction and RME X and RME M the flows of embodied materials that are associated with exports and imports.
- DMC:** Sociometabolic indicator which reflects the consumption patterns in physical terms of the population of each nation and represents the basis used to calculate the Material Footprint of countries. It is calculated as $DMC = DE - PTB$. Where DE is Domestic Extractions and PTB measures the balance between imports and exports in direct physical terms, i.e. without taking into account embodied flows.