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Sustainability Multivariate Analysis of the Energy Consumption of Ecuador Using MuSIASEM and BIPLOT Approach

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Abstract: Rapid economic growth, expanding populations and increasing prosperity are driving up demand for energy, water and food, especially in developing countries. To understand the energy consumption of a country, we used the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) approach. The MuSIASEM is an innovative approach to accounting that integrates quantitative information generated by distinct types of conventional models based on different dimensions and scales of analysis. The main objective of this work is to enrich the MuSIASEM approach with information from multivariate methods in order to improve the efficiency of existing models of sustainability. The Biplot method permits the joint plotting, in a reduced dimension of the rows (individuals) and columns (variables) of a multivariate data matrix. We found, in the case study of Ecuador, that the highest values of the Exosomatic Metabolic Rate (EMR) per economic sector and Economic Labor Productivity (ELP) are located in the Productive Sector (PS). We conclude that the combination of the MuSIASEM variables with the HJ-Biplot allows us to easily know the detailed behavior of the labor productivity and energy consumption of a country.

Keywords: sustainable development; energy consumption; MuSIASEM; HJ-Biplot

1. Introduction

Over the past 50 years, humans have changed ecosystems more rapidly and extensively than in any comparable period of time in human history, largely to meet rapidly growing demands for food, fresh water, timber, fiber, and fuel. This has resulted in a substantial and irreversible loss of diversity of life on Earth [1]. Meeting fundamental human needs while preserving the life-support systems of planet Earth is the essence of sustainable development [2], an idea that was consolidated in 1987 with the publication of the Brundtland report called "Our common future".

In the Brundtland report, sustainable development is defined as "development which meets the needs of current generations without compromising the ability of future generations to meet their own needs" [3]. Under this concept we can talk about Sustainability Science, which focuses on the dynamic interactions between nature and society and offers a more pertinent opportunity to help guide nature-society interactions along sustainable trajectories throughout the globe [2].

It is because of these nature-society interactions that there has been an increase in academic interest in the nexus between food, energy, water, land use and population. This interest is not only because of the individual growing importance of each of the elements, but also a result of recognition, from those working in sustainability science, that it is impossible to analyze the different elements of the nexus one at the time, as if they were independent from each other [4].

The Food and Agriculture Organization of the United Nations (FAO) concept of Water-Energy-Food Nexus explicitly addresses interactions and feedback between human and natural systems. It focuses on the resource base, including both biophysical and socio-economic resources, on which we depend to achieve social, environmental and economic goals pertaining to water, energy and food [5]. The Water-Energy-Food Nexus has emerged as a useful concept to describe and address the complex and interrelated nature of our global resource systems, on which we depend to achieve different social, economic and environmental goals [6].

Rapid economic growth, expanding populations and increasing prosperity are driving up demand for energy, water and food, especially in developing countries. By 2050, the demand for energy will nearly double globally (+80%), with water and food demand estimated to increase by over 50% [7]. Population levels influence the magnitude of energy demand in a straightforward way: the larger the population, the more total energy is required, with the magnitude of this total energy depending on per capita energy consumption [8]. International organizations and national agencies use energy intensity as an indicator of the energy efficiency of a country [9], the more efficient use of energy country-wide will result in less money spent on energy by households, government agencies and industries.

To understand the energy consumption of a country, FAO and other scientific research, we propose to use the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) approach [10–17]. The MuSIASEM is an innovative approach to accounting that integrates quantitative information generated by distinct types of conventional models based on different dimensions and scales of analysis. It builds on several innovative concepts derived from Bioeconomics and the Complex Systems Theory, such as the flow-fund model, multi-purpose grammars and Impredicative Loop Analysis [4].

Given this special feature, MuSIASEM allows us to effectively analyze the factors determining the Energy metabolism of the economy of a country; the main objective of this work is to enrich the MuSIASEM approach with information from multivariate methods in order to improve the efficiency of existing models of sustainability. The Biplot method [18] permits the joint plotting, in a reduced dimension of the rows (individuals) and columns (variables) of a multivariate data matrix. The HJ-Biplot [19] achieves an optimum quality of representation both for the individuals (rows) and the variables (columns); additionally, it plots both of them on the same reference system. This representation is intimately related to Principal Component Analysis (PCA) in the sense that the matrices of variance and covariance are plotted on the two planes that absorb the greatest part of the variability. Finally, we want to show that the combination of the MuSIASEM variables with the HJ-Biplot allows us to easily know detailed behavior of the labor productivity and energy consumption of a country. To do so, we provide a practical case study based on numbers taken from real-world situations and related to the analysis of the sustainability of human societies. The text is divided into 5 main sections: Section 1 contains a brief introduction to the topic, Section 2 presents the case study, database and methodology used, Section 3 contains the main results and Sections 4 and 5 presents the discussions and conclusions of this research.

2. Materials and Methods

2.1. Case Study: Ecuador

Like many others less developed countries in Latin America, Ecuador pursued an outward-oriented model of growth [20] (p. 98). This pattern prevailed from the second half of the nineteenth century to the mid-1960s when import-substituting industrialization began to be pursued. A moderate economic diversification and domestic market expansion took place in the following decades [11].

Ecuador is a South American country, immersed in asymmetric international relations, with high levels of poverty and inequality, fragile levels of education and an economy dependent on the export of primary products, such as crude oil, bananas, shrimp and natural flowers [21]. Some of the fundamental aspects that characterize the historical, economic and environmental development of Ecuador are: loss of original vegetation (deforestation and changes in land use); high rates of population growth; a constant deterioration of biophysical capital, especially of tropical forests, causing the loss of biodiversity; and oil exploitation, which has caused serious social and environmental impacts [22].

Studies based on MuSIASEM have been applied to China [12], Catalonia [13], the UK [14], Spain [23], Chile, Brazil and Venezuela [24], Romania, Bulgaria, Poland and Hungary [9], and Ecuador [10,11]. All of these studies are historical analyzes, while in this work the MuSIASEM is used as an analysis tool for Ecuadorian sustainability in 2015, and we used this result to apply the Biplot method.

2.2. Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM)

Part of this study is based on the MuSIASEM approach. This approach was originally termed as Multi-Scale Integrated Analysis of Societal Metabolism (MSIASM) and later extended to include the interplay between the socioeconomic systems and the ecosystems [25]. It was introduced by Giampietro and Mayumi [26–28] and is inspired in the flow-fund model of Georgescu-Roegen [29,30] and the theory of complex systems of Maturana and Varela [31], among others.

MuSIASEM is an accounting methodology that allows studying biophysical and socioeconomic issues in an integrated manner, both for the level of the society and for the different compartments of that society [32]. In more detail MuSIASEM can be viewed as an operationalization of the Georgescu-Roegen Bioeconomics approach that combines data on flows (exosomatic energy, GDP, etc.) and funds (human time, land use, etc.) associated with the system under study (Ecuador in our case). We chose the unit of administrative and territorial division of Ecuador called a "canton"; a total of 221 cantons were used in this study. Cantons are the second-level subdivisions of Ecuador, below the provinces. The Ecuador system was divided into different sectors and at different levels of hierarchy. Level n was designated as the whole society (Societal Average, SA), Level $n-1$ was divided into paid work sectors (PW) and household sectors (HH) while Level $n-2$ included the paid sectors of agriculture (AG), other productive sectors (PS) and the service and government sector (SG).

With the purpose of studying the energy consumption using the MuSIASEM approach and applying Biplot methods, particularly in this study, we focus on the factors determining the energy metabolism of the economy of Ecuador. In relation to the MuSIASEM approach, we used the variable "hours of human activity" as FUND for the multi-level matrix. The two relevant FLOWS considered in the definition of energy intensity of the economy are: exosomatic energy (expressed in MJ) and added value (expressed in $). That is, we characterize the two flows of exosomatic energy (MJ/h) and added value ($/h) against a multi-level matrix of human activity-across multi-levels. In Table 1 we presented a description of the MuSIASEM variables used in this study and other related studies [11,13,16,33].

Table 1. Description of the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) variables used.

Intensive Variable	Fund/Flow	Name of the Variable	Description	Unit & Calculation
TET	Flow	Total Energy Throughput	Total energy sources that are used for gerating electricity in an economy in one year	Megajoules (MJ) Total energy sources that are used for gerating electricity supply of Ecuador
THA	Fund	Total human activity	Total human time a society has available for conducting different activities	Hours (h) Total population times 8760 h
GDP	Flow	Gross domestic product	Added value generated by an economy in one year	US dollars ($)
ET_i	Flow	Energy Throughput in activity i [1]	Energy sources that are used for gerating electricity in activity i, in one year	Megajoules (MJ) Energy sources that are used for gerating electricity equivalent of energy consumption in each economic sector
HA_i	Fund	Human Activity in activity i	Human time a society has allocated to activity i	Hours (h) Working population in sector i × 46 working weeks × average working hours per week
GDP_i	Flow	Added value generated by activity i	Sum of the value added from the various economic sectors	US dollars ($)
EMR_{SA}	Flow/fund indicator	Exosomatic metabolic rate, average of the society	The amount of energy used per hour of human time for the whole society	MJ/h TET/THA
EMR_i	Flow/fund indicator	Exosomatic metabolic rate for activity i	The amount of energy used per hour dedicated to each sector	MJ/h ET_i/HA_i
ELP_i	Flow/fund indicator	Economic labor productivity for activity i	Added value per hour of working time in activity i	$/h GDP_i/HA_i
EEI	Flow/fund indicator	Economic Energy Intensity	Energy consumption per unit of added value	(MJ/$) TET/GDP

[1] Economic Sectors. To define economic sectors, we used the International Classification Uniform of United Nations. According to this classification, the economy has three main sectors: (1) Agriculture, livestock and fishing sector (AG); (2) Industrial sector (oil and mining, electricity, gas, water and construction) (PS); (3) service and Government sector (SG) [11].

2.3. Database

Gross Domestic Product (GDP) data for the 221 Cantons of Ecuador was obtained from the Central Bank of Ecuador [34]. Energy data was obtained from the Statistics of the Electric Sector-2015 published by Agencia de Regulación y Control de Electricidad of the Government of Ecuador [35]. A yearly hour total of human activity was obtained from population statistics from Instituto Nacional de Estadísticas y Censos de Ecuador (INEC) [36] and in order to allocate hours to the productive sector and the different economic sectors, the employment survey (Encuesta Nacional de Empleo, Desempleo y Subempleo-ENEMDU) was used [37].

2.4. HJ-Biplot Method

The statistical technique used was the HJ-Biplot multidimensional data classification technique [19], which is a variant of the Biplot graphic display proposed by Gabriel [18]. This technique makes it possible to plot the rows and columns of the data matrix as points on a low dimension vectorial space. It has been shown theoretically [19] that the quality of plotting both for individuals and for variables is superior to that achieved with similar techniques. Also, the discriminatory power of this statistical technique has been demonstrated in other studies [38–40].

Let $\boldsymbol{X}$ be a data matrix composed by $\boldsymbol{I}$ individuals measured on $\boldsymbol{J}$ variables. The Singular Value Decomposition (SVD) of $\boldsymbol{X}$ is defined as $\boldsymbol{X} = \boldsymbol{U}\wedge\boldsymbol{V}^{\mathrm{T}}$, where $\boldsymbol{U}$ is a matrix whose column vectors are orthonormal and correspond to the eigenvectors of $\boldsymbol{X}\boldsymbol{X}^{\mathrm{T}}$, $\boldsymbol{V}$ is a matrix whose column vectors are also orthonormal and correspond to the eigenvectors of $\boldsymbol{X}^{\mathrm{T}}\boldsymbol{X}$, and $\wedge$ is a diagonal matrix containing the singular values arranged in decreasing order. The database used in this study was structured in an $\boldsymbol{I} \times \boldsymbol{J}$ data matrix in which the $\boldsymbol{I}$ rows correspond to the 221 Cantos of Ecuador and the $\boldsymbol{J}$ columns correspond to 26 MuSIASEM variables showed in Table 1. The results allow a simultaneous representation of the data and it gets the maximum quality of representation both for the rows and for the columns of the data matrix. In the Biplot representation, the column markers $\boldsymbol{b_j}$ are shown as arrows and the row markers $\boldsymbol{a_i^{\mathrm{T}}}$ as points. The rules for interpreting the HJ-Biplot are: the distances between rows markers are interpreted as inverse similarities (closer individuals are more similar); the lengths of the column vectors approximate the standard deviation of the variables; the cosines of the angles between the column vectors approximate the correlations between variables and row and column markers can be shown in the same Cartesian system with optimal quality of representation [41]. See Figure 1.

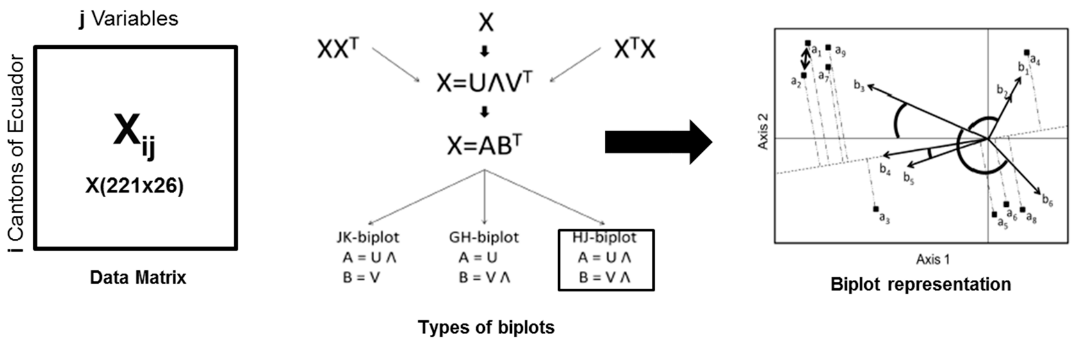


Figure 1. Phases of a Biplot process. Source: Own elaboration using [41].

3. Results

3.1. MuSIASEM Approach

Using the variables presented in Table 1, we can compare the performance of socio-economic system in energy and economic terms.

3.1.1. Level *n*: Whole Society

The Total Energy Throughput (TET) of the provinces of Ecuador is relatively constant in 21 places (below the 5×10^9 MJ), with the exception of Guayas (2.74×10^{10} MJ), Pichincha (1.75×10^{10} MJ) and Manabí (1.49×10^{10} MJ), that correspond to the most populated places of Ecuador according to the INEC. The highest number of industrial establishments, according to the INEC, is located in the provinces of Pichincha (27%) and Guayas (16%), which correspond to the provinces with the highest Gross Domestic Product (GDP). It is important to note that of the 221 cantons of Ecuador, Guayaquil (in Guayas) and Quito (in Pichincha) contribute 42.8% of the country's GDP. See Figure 2.

The economic Energy Intensity (EEI) accounts for energy consumed per unit of value added generated. The EEI in Ecuador is relatively constant, with a peak of 2649.54 MJ/$ in Manabí and the lower value in Orellana (131.70 MJ/$). See Figure 3.

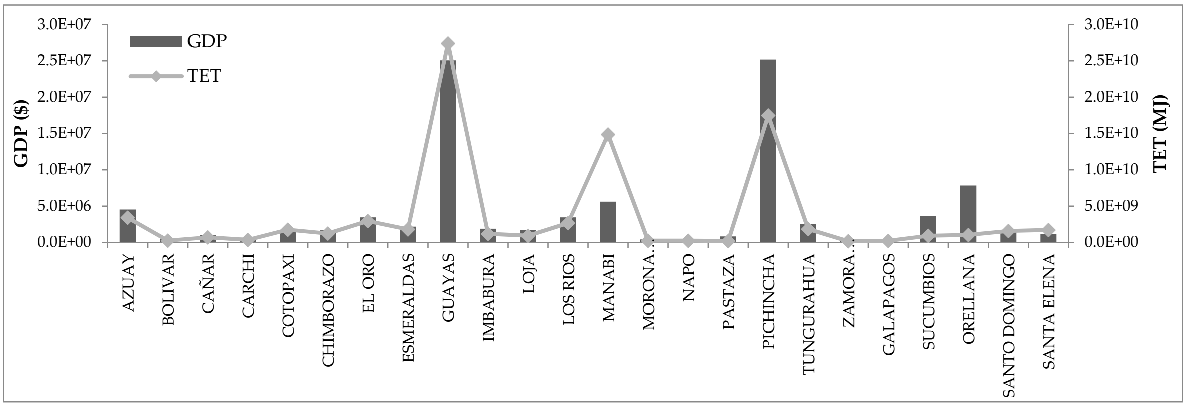


Figure 2. Gross Domestic Product (GDP) and Total Energy Throughput (TET) of the 24 provinces of Ecuador. Source: Own elaboration.

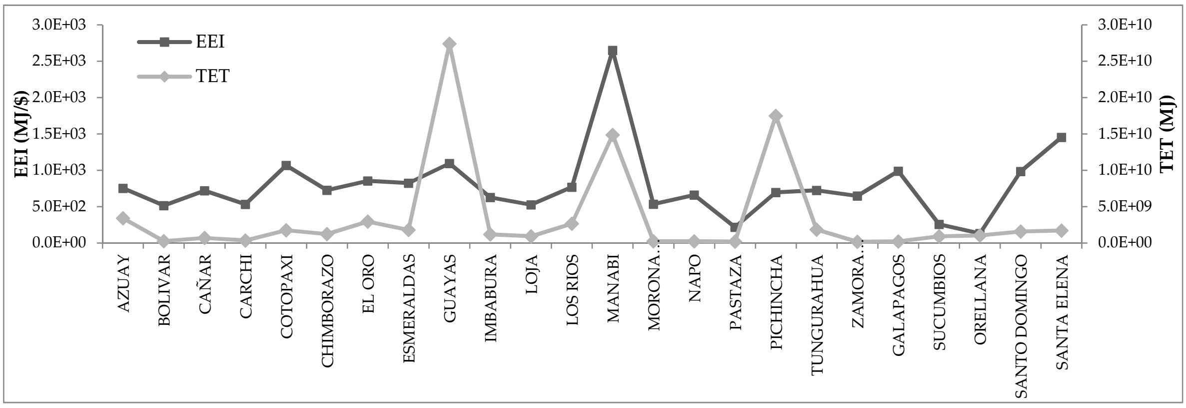


Figure 3. Economic Energy Intensity (EEI) and Total Energy Throughput (TET) of the 24 provinces of Ecuador. Source: Own elaboration.

The Total Human Activity (THA) represent the total human time available for conducting different economic activities and the human activity in the household. The THA of Ecuador is higher in the most populated province and with the highest number of industrial establishments, like Guayas (3.19×10^{10} h) and Pichincha (2.26×10^{10} h). See Figure 4.

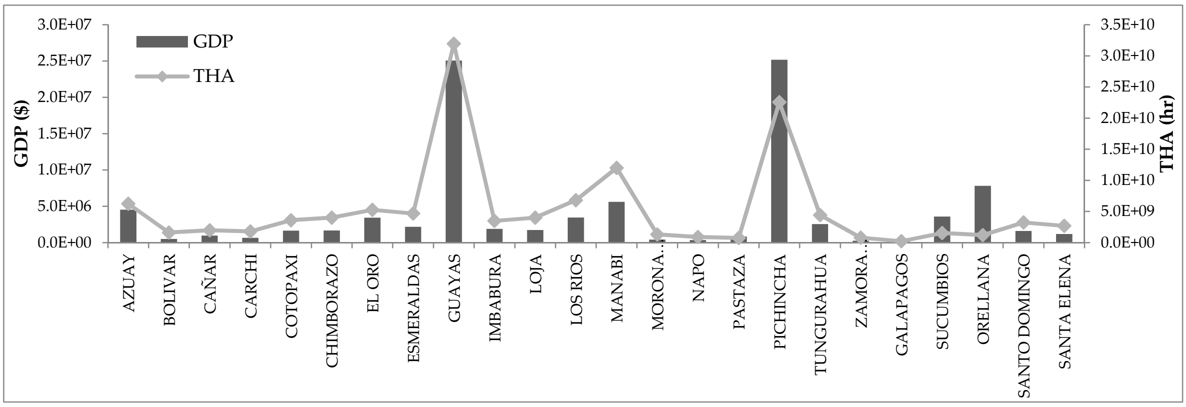


Figure 4. Gross Domestic Product (GDP) per capita and Total Human Activity (THA) of the 24 provinces of Ecuador. Source: Own elaboration.

When looking at the Exosomatic Metabolic Rate (EMR_{SA}) performance of the provinces of Ecuador we see a peak in Manabí of 1.24 MJ/h, this is because energy consumption of the Manabí grew faster than its population, according to the INEC [42], Manabí has a population growth of 1.60%, while Guayas and Pichincha, which are the most populated places of Ecuador, have a population growth of 1.08% and 0.84%, respectively. See Figure 5.

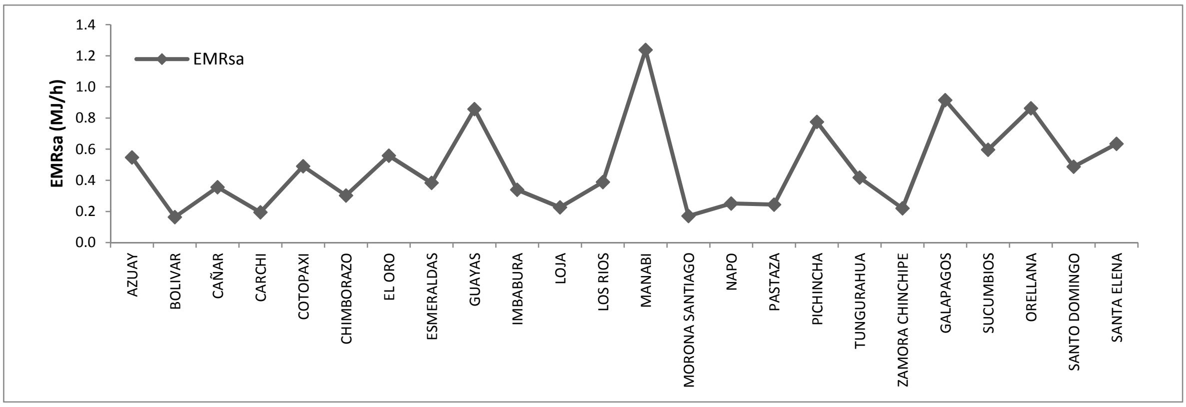


Figure 5. Exosomatic Metabolic Rate (EMR_{sa}) of the 24 provinces of Ecuador. Source: Own elaboration.

3.1.2. Level $n-1$: Paid Work Sectors (PW) and Household Sectors (HH)

The Exosomatic Metabolic Rate of the productive sector (EMR_{PW}) can be used as a proxy for the level of capitalization of the economy. On the other hand, the Exosomatic Metabolic Rate of the households (EMR_{HH}) can be used as a proxy for the level of material standard of living of households [43]. When looking at the data of Ecuador, we see that the EMR_{PW} is high in Guayas with 163.44 MJ/h, the economic structure of Guayas is based on the agricultural, fishing, manufacturing, commercial and construction sectors. The most important economic sector in Guayas is the manufacturing sector; this sector introduced machinery and technology and therefore boosted productivity. The highest metabolic pattern of households in Ecuador is located in Manabí with 35.18 MJ/h, showing that the largest increase in energy consumption was directed to increasing the material of standard living. This confirms that a large fraction of the increase in energy consumption was not oriented towards capitalization in the productive sectors (and then towards increased labor productivity) but was oriented towards increasing consumption levels in households, a fact that resulted in a decreased income per hour worked in productive sectors [33]. See Figure 6.

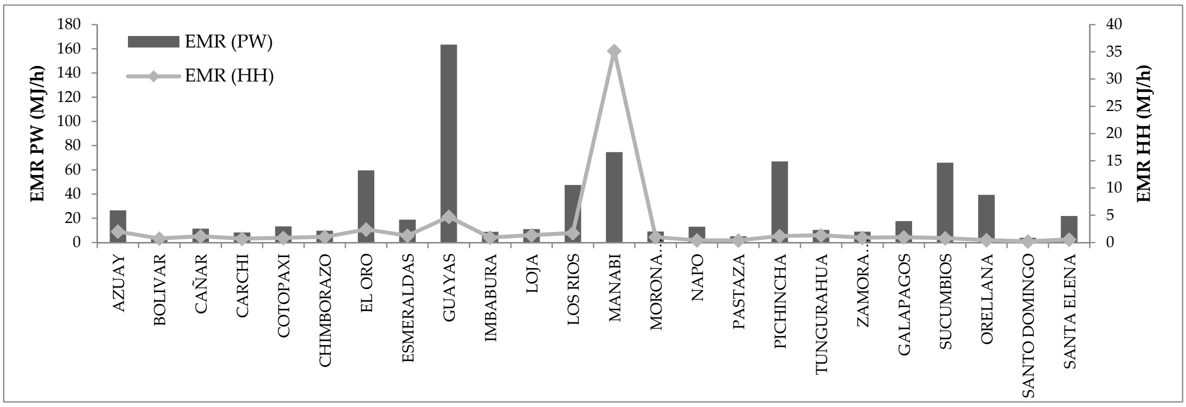


Figure 6. Exosomatic Metabolic Rate of the productive sectors (EMR_{PW}) and the households (EMR_{HH}) of the 24 provinces of Ecuador. Source: Own elaboration.

Figure 7 shows the Economic Labor Productivity (ELP_{PW}), where Sucumbíos and Orellana have the highest value in ELP_{PW}, 0.28 ($/h) and 0.27 ($/h) respectively. This is because Sucumbíos (Cantons of Putumayo and Cuyabeno) and Orellana (Canton of La Joya de los Sachas) belong to the oil regions of Ecuador.

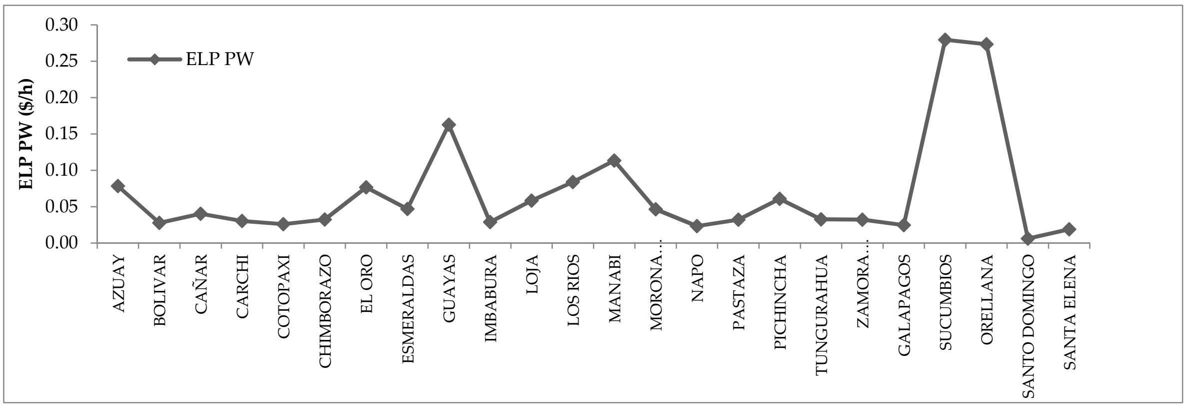


Figure 7. Economic Labor Productivity of the productive sectors (ELP_{PW}) of the 24 provinces of Ecuador. Source: Own elaboration.

3.1.3. Level $n-2$: Productive Sectors

The highest values of Exosomatic Metabolic Rate per economic sector (EMR) in Ecuador are located in the Productive Sector (PS), with the exception of Los Ríos, Sucumbíos and Orellana; these three places have high values of EMR in the Service and Government Sector (SG). In Figure 8 we can see that the three economic sectors peak in Guayas; in this place the PS Sector (EMR_{PS}), composed of industrial activities with a high material requirement and energy demand, has the highest level of EMR per hour (307.61 MJ/h). This is because the most important economic sector in Guayas is the manufacturing sector. Also the Services and Government Sector (SG) has an EMR per hour of the 222.80 MJ/h and the Agriculture Sector (AG) has an EMR per hour of the 70.94 MJ/h.

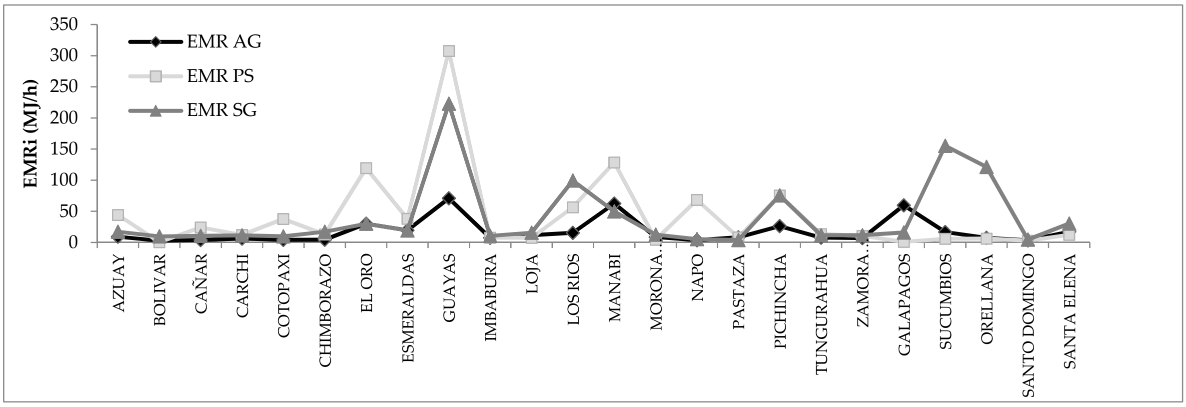


Figure 8. Exosomatic Metabolic Rate per economic sector (EMR_{AG}, EMR_{PS} and EMR_{SG}) of the 24 provinces of Ecuador. Source: Own elaboration.

Finally, Economic Labor Productivity is represented in Figure 9. The highest values of labor productivity in the SG sector are in: Bolivar (0.05 $/h), Cañar (0.07 $/h), Cotopaxi (0.04 $/h), Chimborazo (0.06 $/h), El Oro (0.10 $/h), Loja (0.11 $/h), Los Ríos (0.10 $/h), Manabí (0.14 $/h), Morona Santiago (0.09 $/h), Napo (0.04 $/h), Pichincha (0.06 $/h), Tungurahua (0.06 $/h), Zamora Chichimpe (0.07 $/h) and Galápagos (0.03 $/h); and the highest values of labor productivity in the PS sector are in: Azuay (0.12 $/h), Carchi (0.04 $/h), Esmeraldas (0.05 $/h), Guayas (0.19 $/h), Pastaza (0.08 $/h), Sucumbíos (1.06 $/h), Orellana (1.25 $/h), Santo Domingo (0.01 $/h) and Santa Elena (0.03 $/h). The PS sector has two peaks, in Orellana and Sucumbíos, as previously mentioned this is because both places belong to the oil region of Ecuador.

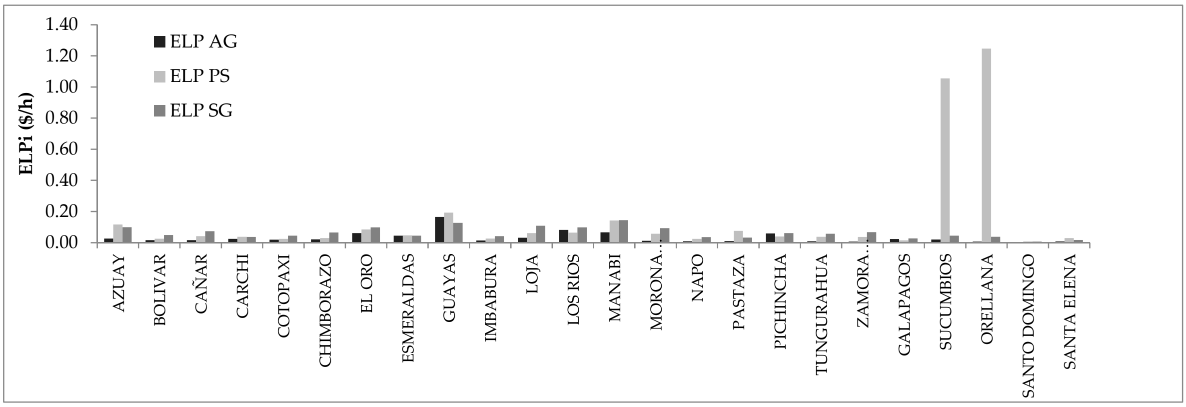


Figure 9. Economic Labor Productivity per economic sector (ELP_{AG}, ELP_{PS} and ELP_{SG}) of the 24 provinces of Ecuador. Source: Own elaboration.

3.2. Biplot Method

With the objective to enrich the MuSIASEM approach with information from multivariate methods we applied the HJ-Biplot to our $\boldsymbol{I} \times \boldsymbol{J}$ data matrix ($\boldsymbol{I}$ rows correspond to the 221 Cantos of Ecuador and the $\boldsymbol{J}$ columns correspond to 26 MuSIASEM variables) using the R package BiplotbootGUI (Bootstrap on Classical Biplots and Clustering Disjoint Biplot) developed by Ana Belen Nieto Librero and Purificación Galindo Villardón [44].

The first three axes explain **64.45%** of variability of the data, achieving **51.22%** in the first principal plane (Table 2). The overall goodness of fit as a percentage of correct classification in the Biplot is **64.46%**, so the two dimensional solution is sufficient to explore the main features of the data.

Table 2. Eigenvalues and variability % explained.

Axes	Eigenvalue	% of Variance	Cumulative %
1	46.45	37.72	37.72
2	28.14	13.84	51.56
3	27.16	12.89	64.45

Source: Own Elaboration using BiplotbootGUI.

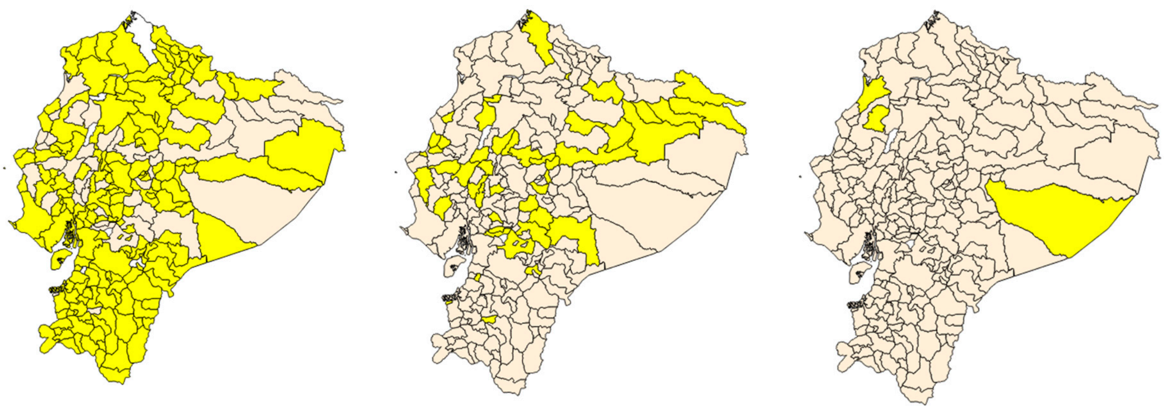
Table 3 shows the relative contribution of the q-th factor to column element j for the MuSIASEM variables, the variables that characterize axis 1 (variables that receive a strong contribution of axis 1 and low in axis 2) are: Total Human Activity (THA), Human Activity in Paid Work (HA_{PW}), Human Activity in Household (HA_{HH}), Human Activity per economic sector (HA_{AG}, HA_{PS} and HA_{SG}), Total Energy Throughput (TET), Energy Throughput in Paid Work (ET_{PW}), Energy Throughput per economic sector (ET_{SG}, ET_{AG} and ET_{PS}), Exosomatic Metabolic Rate in Agriculture sector (EMR_{AG}), Gross Domestic Product (GDP), Gross Domestic Product in Service and Government sector (GDP_{SG}), Gross Domestic Product in Agriculture sector (GDP_{AG}) and Economic Labor Productivity in Agriculture sector (ELP_{AG}). The variables that characterize axis 2 are: Exosomatic Metabolic Rate in Service and Government sector (EMR_{SG}), Exosomatic Metabolic Rate in Productive sector (EMR_{PS}), Exosomatic Metabolic Rate in Paid Work (EMR_{PW}), Gross Domestic Product in Productive sector (GDP_{PS}), Economic Labor Productivity in Paid Work (ELP_{PW}), Economic Labor Productivity in Service and Government sector (ELP_{SG}) and Economic Labor Productivity in Productive sector (ELP_{PS}). Finally, the variables that characterize axis 3 are: Energy Throughput in Household (ET_{HH}), Exosomatic Metabolic Rate average of the society (EMR_{SA}) and Exosomatic Metabolic Rate in Household (EMR_{HH}).

Table 3. Relative contribution of the q-th factor to column element ***j***.

MuSIASEM Variable	Axis 1	Axis 2	Axis 3
THA	916.56	82.8	0.64
HA_{AG}	828.5	169.2	2.3
HA_{PS}	939.03	59.48	1.49
HA_{SG}	931.5	67.47	1.03
HA_{PW}	919.72	78.96	1.32
HA_{HH}	916.25	83.16	0.59
TET	447.45	124.19	428.36
ET_{HH}	104.39	122.34	773.27
ET_{PW}	947.32	50.38	2.3
ET_{SG}	859.8	136.49	3.71
ET_{AG}	926.39	71.8	1.81
ET_{PS}	987.75	9.38	2.87
EMR_{SA}	46.08	318.75	635.17
EMR_{HH}	11.51	177.46	811.03
EMR_{SG}	90.3	867.63	42.07
EMR_{AG}	979.83	20.01	0.16
EMR_{PS}	296.8	684.05	19.15
EMR_{PW}	246.17	750.85	2.98
GDP	634.41	148.9	216.69
GDP_{SG}	946.66	52.39	0.94
GDP_{PS}	201.96	438.08	359.95
GDP_{AG}	941.74	54.4	3.86
ELP_{PW}	39.6	633.93	326.47
ELP_{SG}	403.17	557.43	39.4
ELP_{PS}	24.01	617.26	358.73
ELP_{AG}	668.27	329.34	2.39

Source: Own Elaboration using BiplotbootGUI package.

Using the relative contribution of the q-th factor to row element ***i*,** the places (Cantons) that characterize axis 1 are showed in Figure 10a, the places that characterize axis 2 are showed in Figure 10b and the places that characterize axis 3 are showed in Figure 10c.



(**a**) (**b**) (**c**)

Figure 10. The relative contribution of the q-th factor to row element **i**: (**a**) Cantons of Ecuador that characterize axis 1; (**b**) Cantons of Ecuador that characterize axis 2; (**c**) Cantons of Ecuador that characterize axis 3. Source: Own Elaboration using QGIS 2.18.4.

In the Biplot representation, the MuSIASEM variables are shown as arrows (vectors) and the cantons as points. The cosines of the angles are useful to interpret how variables are related to each gradient. In summary, we have found two main gradients. The horizontal axis is related to: ET_{PS}, EMR_{AG}, ET_{PW}, GDP_{SG}, GDP_{AG}, HA_{PS}, HA_{SG}, ET_{AG}, HA_{PW}, THA and HA_{HH}. Then, the first gradient is associated with: the Energy Throughput per economic sector, Total Human Activity, Human

Activity in Productive sector and Service and Government sector, Human activity in Household and Gross Domestic Product in Agriculture sector and Service and Government sector. The points (cantons) located on the right side of factorial axis 1 account more of MuSIASEM indicators related to the first gradient then those located on the left side. The second gradient (vertical axis) comprises the MuSIASEM variables: ELP_{PS}, ELP_{PW}, EMR_{HH} EMR_{PW}, EMR_{PS} and EMR_{SG}. This gradient is associated with the Economic Labor Productivity and Exosomatic Metabolic Rate. The points (cantons) located above the factorial axis 1 have greater values for these MuSIASEM variables as opposed to those located at the bottom. See Figure 11.

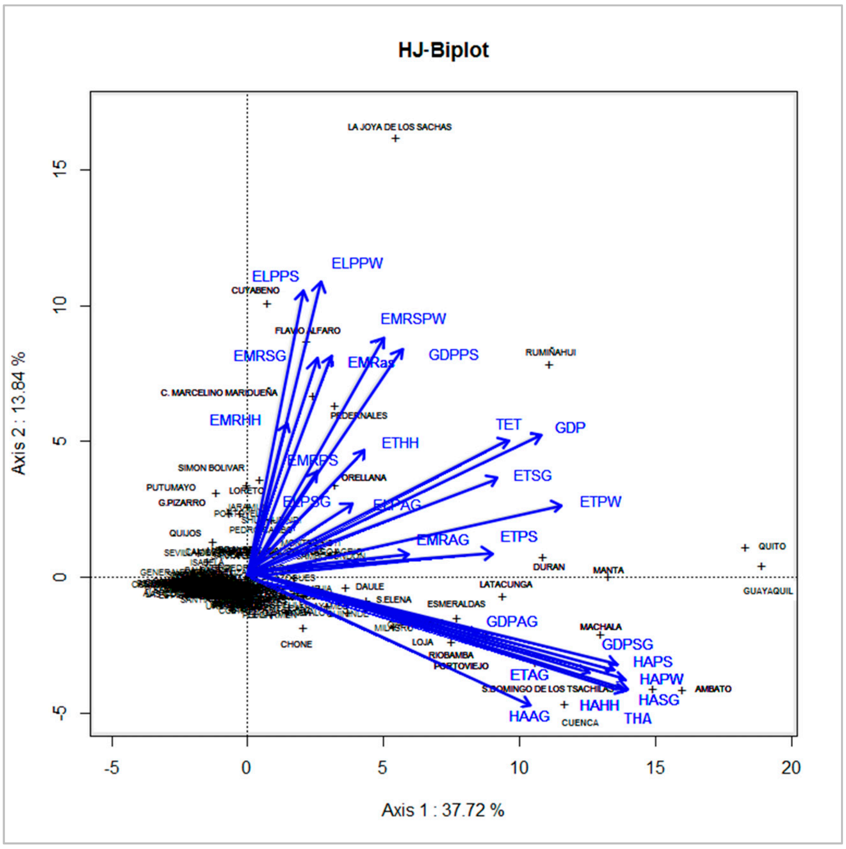


Figure 11. HJ-Biplot representation of the data matrix. Source: Own Elaboration using BiplotbootGUI R Package.

3.3. *Added Value of Using HJ-Biplot Together with MuSIASEM Approach*

When we reviewed the literature on the MuSIASEM approach, we realized that most of the studies are historical analyzes of a country or comparative analyzes between countries. One of the main objectives of this research was to know the detailed behavior of the electric energy consumption of a country, for that reason, we chose the unit of administrative and territorial division of Ecuador called a "canton"; a total of 221 cantons were used in this investigation.

For the first time, the MuSIASEM approach was applied to a group of more than 200 individuals (cantons in our case), but as you can see in section 3 of the results, we can only present the results at the provincial level (first-level territorial subdivisions of Ecuador), because with the MuSIASEM approach we cannot put in one graphic the 221 individual cantons and the 26 variables and evaluate the behavior of the 221 individual cantons at the same time. So for that reason we decided to apply multivariate statistics tools using the variables described in the MuSIASEM methodology. The Biplot method permits the joint plotting, in a reduced dimension of the rows (221 cantons) and columns (26 MuSIASEM variables). Finally the added value of the HJ-Biplot to the MuSIASEM approach is the statistical multivariate analysis; we can see the explained variance of the analysis, correlation between variables and cantons with similar characteristics.

4. Discussion

The objective of this investigation was to enrich the MuSIASEM approach with information from multivariate methods (HJ-Biplot in our case), and it showed that the combination of both methods allows us to easily know the detailed behavior of the labor productivity and energy consumption of a country.

With the MuSIASEM approach we cannot put the 221 individual and the 26 variables in one graphic, whereas with the HJ-Biplot method it is possible to plot the rows (individuals) and columns (variables) of the data matrix as points on a low dimension vectorial space.

In the HJ-Biplot axis 1 was related to: ET_{PS}, EMR_{AG}, ET_{PW}, GDP_{SG}, GDP_{AG}, HA_{PS}, HA_{SG}, ET_{AG}, HA_{PW}, THA and HA_{HH}; this means that places located on the right side of factorial axis 1 have higher values of the MuSIASEM indicators then those located on the left side of the Biplot representation, for example, in Figure 11, places like: Orellana (Canton of Orellana Province), Rumiñahui (Canton of Pichincha Province), Machala (Canton of El Oro Province), Ambato (Canton of Tungurahua Province), Santo Domingo de los Tsáchilas (Canton of Santo Domingo de los Tsáchilas Province), Portoviejo (Canton of Manabí Province), Manta (Canton of Manabí Province), Durán (Canton of Guayas Province), Latacunga (Canton of Cotopaxi Province), Loja (Canton of Loja Province), Esmeraldas (Canton of Esmeralda Province), Cuenca (Canton of Azuay Province), Quito (Canton of Pichincha Province) and Guayaquil (Canton of Guayas Province).

One of the reasons why the Canton of Guayaquil, and consequently the province of Guayas, have high values in the MuSIASEM variables related to the THA, GDP and EMR, in comparison with the other cantons, is because according to Central Bank of Ecuador [45] and the Provincial Government of Guayas [46] the Guayaquil canton is the one with the greatest development in infrastructure and its tourist plant, and also the city with the highest influence on the GDP of Guayas (province with the highest contribution to the productive activity of Ecuador). According to the results of the population census conducted by the INEC, Guayaquil is the most populated canton of Ecuador with 2,350,915 people [47]. See also Figure 2.

Another canton with high values in the MuSIASEM variables related to the THA, GDP and EMR, in comparison with the other cantons, is the capital city of Ecuador, Quito; it is the second most populated canton of the country with 2,239,191 people and belongs to the Province of Pichincha. Pichincha, according to the INEC, has the highest number of industrial establishments and contributed 23.9% of the GDP of the country. The provinces of Orellana (8.9%), Manabí (5.9%), Azuay (4.9%), Sucumbíos (4.5%) and Los Ríos (3.5%) followed in importance of their contribution to the GDP of Ecuador.

In the HJ-Biplot axis 2 was related to: ELP_{PS}, ELP_{PW}, EMR_{HH} EMR_{PW}, EMR_{PS} and EMR_{SG}. This axis is associated with Economic Labor Productivity (ELP) and the Exosomatic Metabolic Rate (EMR) of Ecuador. Previous energetic analyses of the economic process [11,48–50] have indicated a clear link between the ELP and EMR. Places (cantons) with high values of ELP will have high values in EMR. For example, in Figure 11, places like La Joya de los Sachas (Canton of Orellana Province), Cuyabeno (Canton of Sucumbíos Province), Flavio Alfaro (Canton of Manabí Province) and Coronel Marcelino Maridueña (Canton of Guayas Province). Las Joyas de los Scahas and Cuyabeno belongs to the oil regions of Ecuador and Las Joyas de los Sachas has the highest daily oil production of Ecuador, according to Petroecuador [51].

According to Falconi in the "Integrated Assessment of the Recent Economic History of Ecuador" article, Economic Labor Productivity of agriculture remained well below the values of ELP reached by the other economic sectors [11], as we showed in Figure 9.

5. Conclusions

The main conclusions reached in our analysis are the following:

1. The use of the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) approach with the HJ-Biplot allows us to easily know the detailed behavior of the labor productivity and energy consumption (in our case) of a country.

2. With the MuSIASEM approach we cannot put all of the 221 individual cantons and 26 variables in one graphic, whereas with the HJ-Biplot method it possible to plot the rows (individuals) and columns (variables) of the data matrix as points on a low dimension vectorial space. With the combination of the two approaches we can easily know the detailed behavior of the labor productivity and energy consumption (in our case) of a country.
3. In the case of Ecuador, using HJ-Biplot we found that the first gradient of MuSIASEM indicators are associated with: the Energy Throughput per economic sector, Total Human Activity, Human Activity in Productive sector and Service and Government sector, Human activity in Household and Gross Domestic Product in Agriculture sector and Service and Government sector; and the second gradient is associated with Economic Labor Productivity and the Exosomatic Metabolic Rate.
4. In the HJ-Biplot, axis 2, associated with Economic Labor Productivity (ELP) and the Exosomatic Metabolic Rate (EMR) of Ecuador, indicated a clear link between ELP and the EMR. Places (cantons) with high values of ELP will have high values in EMR.
5. We found that the cantons of Guayaquil and Quito have high values in the MuSIASEM variables related to the THA, GDP and EMR, in comparison with the other cantons.
6. In Ecuador the highest values of the Exosomatic Metabolic Rate per economic sector (EMR) and Economic Labor Productivity are located in the Productive Sector (PS).
7. The highest metabolic pattern in Exosomatic Metabolic Rate (EMR_{HH}) of households in Ecuador is located in Manabí province, showing that the most of the increase in energy consumption was directed to increasing the material of standard living.

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