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Environmental Sustainability in South America

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Abstract: The purpose of this article is to determine the similarities in the context of environmental practices and sustainability of twelve South American countries and compare the environmental sustainability performance with six principal components. A multivariate analysis as a hierarchical method was carried out with seventeen sustainable environmental indicators, using official secondary data sources, namely the databases of ECLAC (Economic Commission for Latin America and the Caribbean), applying eigenvectors and eigenvalues from the correlation matrix and Ward's method with squared Euclidean distances.

The results suggest that the initial jumps in terms of distance are small, so the twelve countries analyzed in the study are grouped into five clusters. Deepening then in the perspective of the characteristics of each cluster, CL1: Colombia, Venezuela, Suriname, Argentina and Bolivia; CL2: Guyana, Paraguay, Uruguay and Peru; CL3: Brazil; CL4: Ecuador; CL5: Chile. The research highlights significant differences among these South American countries, clustering those with similar patterns of behavior and identifying the best performers. We argue there is a need to protect and promote biodiversity, raise awareness of the importance of environmental sustainability and support the impacts of climate change. Argentina, Uruguay and Chile face severe water scarcity problems, and temperatures have risen in all the countries, but especially in Brazil, Colombia, Ecuador, Paraguay, Suriname and Venezuela.

Keywords: environmental sustainability, South America, multivariate analysis, sustainable environmental indicators.

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La sostenibilidad medioambiental en América del Sur

Resumen: El propósito de este artículo es determinar las similitudes en el contexto de las prácticas ambientales y la sostenibilidad de doce países de América del Sur, y comparar el desempeño de la sostenibilidad ambiental con seis componentes principales. Se realizó un análisis multivariado como método jerárquico con diecisiete indicadores ambientales sostenibles; se consultaron fuentes de datos oficiales secundarios, a saber, la base de datos de la CEPAL (Comisión Económica para América Latina), aplicando el vector propio y los valores propios de la matriz de correlaciones y el método de Ward con distancias euclidianas al cuadrado.

Los resultados sugieren que los saltos iniciales en términos de distancia son pequeños. En consecuencia, los doce países analizados en este estudio se agrupan en cinco clusters. Profundizando luego en la perspectiva de las características de cada cluster, CL1: Colombia, Venezuela, Surinam, Argentina y Bolivia; CL2: Guyana, Paraguay, Uruguay y Perú; CL3: Brasil; CL4: Ecuador; CL5: Chile. La investigación pone de relieve diferencias significativas entre estos países sudamericanos, agrupando a los que presentan patrones de comportamiento similares e identificando a los que obtienen mejores resultados. Argumentamos que hay que proteger y fomentar la biodiversidad, y concienciar sobre la importancia de la sostenibilidad medioambiental y apoyar el impacto del cambio climático. Argentina, Uruguay y Chile se enfrentan a graves problemas de escasez de agua y las temperaturas han aumentado en todos los países, pero especialmente en Brasil, Colombia, Ecuador, Paraguay, Surinam y Venezuela.

Palabras clave: sostenibilidad ambiental, América del Sur, análisis multivariante, indicadores ambientales sostenibles.

Códigos JEL: P48, C38, Q1, H11, N56.

INTRODUCTION

In considering global sustainability, it is necessary to address human, animal, plant and environmental health as inseparable aspects of an interlinked challenge (United Nations Environment Program [UNEP], 2022). The vital role played by environmental, social and economic sustainability is acknowledged by academics and policymakers alike. Environmental sustainability theory argues that for an organization to gain and maintain sustainable competitive advantage, it must balance economic, environmental and social interests, and recognize current and future needs in each of these areas (Olafsson et al., 2014).

In this context, benchmarking is the application of uniform measures to assess performance. Successful benchmarking of environmental sustainability performance requires adequate disclosure of information, regarding all levels of governance (Alcaraz-Quiles et al., 2014). Relevant aspects of environmental performance include climate change, air quality, waste generation, water quality, water resources, forest resources, energy resources (Ponomarenko et al., 2022), biodiversity and environmentally-related taxes. These areas of concern have been addressed by many public administrations, and various international conventions in this respect have been approved and ratified in recent years (Organisation for Economic Co-operation and Development [OECD], 2022). Focusing both on individual countries and on continental regions, international organizations have sought to evaluate environmental sustainability performance, emphasizing the need to strengthen efforts to mitigate and adapt to climate change and urban pollution (Gómez Peláez et al., 2020; Klumpp et al., 2023), and to protect and restore the natural world.

This paper examines and compares the environmental sustainability performance of twelve South American countries. Previous research in this area is limited in its instrumental and rationalistic conceptualization and very few cross-country benchmarking performance case studies have been presented. Moreover, few studies have reported on the current understanding of environmental sustainability (Crabb & Leroy, 2008; Da Cruz & Marques, 2014; Ammons & Roenigk, 2015), or on policies, agreements and successes in this area. In this paper, we argue that environmental sustainability performance depends on ecosystem services at local, national and international scales, and that governance systems have a duty of care towards environmental infrastructure (Olafsson et al., 2014), including information disclosure on sustainability-related outcomes.

Assessing the environmental outcomes of sustainability initiatives is a complex issue. The broad scope of the Economic Commission for Latin America and the Caribbean Statistical Databases and Publications (CEPALSTAT) indicators reflect the UN's aim to enhance environmental protection policies worldwide and help measure national progress in South America. Especially important among these indicators are the six principal components (PC) or constructs that are characterized by 17 environmental indicators (Table 1).

With these considerations in mind, this paper aims to evaluate the environmental sustainability performance of twelve South American countries, considering data published in 2019. According to Alcaraz-Quiles et al. (2014), an evaluation of national performance in implementing sustainable development policies and of the corresponding legal measures adopted would lack practical application without reference to the sustainable development guidelines that have arisen from considerations of global governance. In the present analysis, therefore, we evaluate environmental sustainability performance to better understand the complex modus operandi of international organizations, countries and regions in developing new indicators of environmental phenomena and their subnational, national and supranational effects.

The Global Reporting Initiative (GRI, 2022) provides the world's most widely used standards – the GRI Standards – for sustainability reporting. Specific environmental areas are commonly assessed in terms of the key indicators proposed by the OECD (2022), together with the World Development Indicators that have been published by the World Bank since the 1960s. The use of these and other indices of environmental sustainability informs policymakers and society at large of the relationships and trade-offs among the environmental, social and economic dimensions of sustainability (Goodland, 1995).

In this paper, we focus on six principal components of environmental sustainability: secondary energy production and change in energy intensity, the proportion of marine protected areas for the conservation of biodiversity, the contribution to the persistence of marine biodiversity, the proportion of areas dedicated to the conservation of terrestrial and marine biodiversity, the impact of global warming, and measures taken to address pollution and overexploitation of the oceans.

After critically discussing the core ideas of environmental sustainability, we elaborate on the main features highlighted in our review of the literature, including a subsection of studies focused on the context of South America. Finally, we identify and discuss the significant differences observed among these countries in terms of their environmental sustainability performance, and construct a profile to define the results obtained, in five clusters.

In short, this paper reveals patterns of behavior in the countries considered, according to the different initiatives adopted, and illustrates the benefits of benchmarking these outcomes. This research has the following practical implications: we identify the best performing countries, thus facilitating the creation of benchmarks for their neighbors, and suggest possible environmental performance improvements, hence strengthening sustainability. In this regard, Ammons et al. (2001) and Rutherford (2000), among others, have commented that effective benchmarking requires that uniform measures be applied. In another study, Alcaraz-Quiles et al. (2014) considered the disclosure of information about sustainability by different government agencies.

The literature on environmental sustainability in South America is mainly descriptive and non-academic, a research gap that the present study seeks to fill. Accordingly, we address the following research questions:

RQ1: How have these 12 South American countries evolved in terms of environmental sustainability and how are they now positioned regarding the provision of indicators to support benchmarking?

RQ2: What similarities and differences can be observed among the indicators of environmental sustainability in these countries?

RQ3: What behavior patterns can be observed regarding the use of environmental sustainability indicators?

RQ4: Can some countries be identified as benchmarks for others, in terms of their environmental sustainability behavior?

The rest of this paper is organized as follows. In the next section, we present a literature review of environmental sustainability in the 12 countries considered. We then conduct an empirical analysis, explaining the data and methodology used. This is followed by a presentation and discussion of the findings obtained. Finally, we summarize the main conclusions drawn.

LITERATURE REVIEW

Environmental Sustainability

The UNEP publishes data on 30 major indicators, including air pollution, climate change, greenhouse gases, biodiversity, energy and minerals, forests, governance and inland water resources. According to the UNEP report (2022), the devastating impacts of climate change, pollution, waste and the degradation of the natural world have been compounded by widening inequality, conflict in Ukraine and elsewhere and rising prices for food and energy. And as always, the poorest and most vulnerable populations have been hardest hit by impacts such as drought, flooding, wildfires, and the loss of biodiversity.

Numerous academic studies and environmental sustainability institutions, including Sun et al. (2020), Olafsson et al. (2014) and Alcaraz-Quiles et al. (2014), have considered the measurement and assessment of sustainability performance, noting that the selection of appropriate indicators is a dynamic question that must be addressed in accordance with the requirements and priorities assumed. If an accurate evaluation can be achieved, this will enable policymakers to identify and apply the policy measures needed to strengthen environmental sustainability in the context considered. In response to this perceived need, international organizations such as the OECD (2022), the World Bank (2022), GRI (2022) and UNEP (2022) have developed performance indicators to assess environmental sustainability.

The environmental sustainability indicators published by CEPALSTAT (2022), the statistical databases and publications portal of ECLAC, are the metrics most used to measure specific areas of physical conditions, ecosystems and biodiversity, including environmental quality, energy resources, biological resources, water resources, atmospheric emissions, waste production and disposal, and natural events and disasters. Ecological indicators and 3 dimensions assess sustainability in 11 Latin American countries (Toumi et al., 2017).

In addition, consideration must be given to novel challenges such as the role of AI and its impact on sustainability action and governance as a referent in policies for international sustainability to ecological modernization, the green government movement and civic environmentalism need consideration (Francisco & Linnér, 2023). These emerging interactions have showed the relation of environmental sustainability to Corporate Social Responsibility (CSR) practices and green innovation (Shahzad et al., 2020).

Environmental Sustainability in South America

In this section, we review the literature on environmental sustainability issues as they affect diverse countries in South America.

The challenge of assessing environmental performance has been taken up by many public administrations and international organizations, using appropriate indicators of environmental phenomena and their impacts, whether regional, national or supranational. Among them, the OECD Key Indicators (2022) are commonly used to measure specific areas of environmental concern, such as climate change, air quality, waste generation, water quality, water resources, forestry resources, energy resources, biodiversity and environmentally related taxation. In addition, the World Bank has proposed World Development Indicators (WDI) focusing on agriculture, climate, energy and mining, environment, urban and rural development, water and sanitation, among other areas. These indicators can be analyzed to reveal a country's progress towards achieving the environmental goals set out in the 2030 Agenda for Sustainable Development (World Bank, 2022). The GRI Standards are currently the most widely used measures of sustainability reporting and corporate accountability.

According to Sun et al. (2020), the above indicators are an invaluable resource for policymakers, providing them with meaningful information for monitoring and comparing the outcomes of procedures adopted. Another useful tool is the 2022 Environmental Performance Index (EPI), which shows, for example, that Nordic countries score highly for sustainability, via longstanding investments in policies to protect environmental health, preserve biodiversity and natural habitats, conserve natural resources and decouple greenhouse gas emissions from economic growth. Denmark tops the 2022 EPI rankings, thanks to its strong performance across nearly all the issues considered.

Gallego-Álvarez et al. (2018) used the EPI indicators and the HJ-Biplot multivariate analysis methodology to analyze the variables that might influence microeconomic policies and their effect on investment in 24 Latin American countries. These authors concluded that Argentina, Chile and Brazil were the countries in this region most concerned about climate change. Hermosa et al. (2024) propose e-AI based on Global Reporting Initiative GRI survey, enhancing governance and website accessibility for South American disclosure. In recent years, the forest area has shrunk dramatically and became fragmented, due in part to the prolonged drought that has affected many parts of South America, for example, Central Chile from 2010 to 2017. This deforestation and the consequent loss of biodiversity is just one of many negative effects of climate change. Miranda et al. (2020) discussed the effects of geographical variation and forest type as indicators of drought, using data from the MODIS satellite sensor, and temporal trends in the

Normalised Difference Vegetation Index in a highly threatened Mediterranean landscape of South America.

Water resources are of vital importance, both for the environment in general and for human life in particular (Shiklomanov, 1998). South America has almost one third of the world's renewable water resources, and Brazil, Colombia and Peru are among the top ten countries in this respect (Global Water Partnership [GWP], 2022). Nevertheless, several regions, for example in Argentina, Uruguay and Chile, are subject to severe water scarcity, causing crop losses, jeopardizing food security and human health and endangering ecosystems (United Nations, 2023). Furthermore, Ecuador, Paraguay, Bolivia and Venezuela present high levels of eutrophication (excessive presence of nutrients such as phosphorus and nitrogen) due to uncontrolled agricultural activities and wastewater discharge.

Paredes-Beltran et al. (2021) applied the Water Availability and Adaptation Policy Analysis (WAAPA) model to evaluate water storage and its influence on the river systems of South America. The study results show that water availability is greater in the southeast, which the authors suggest is due to the widespread development of hydraulic infrastructure in this area of the continent. Reflecting this understanding, several countries have announced their intention to build hundreds of new dams, for a variety of purposes. Darré et al. (2019) discussed experiences and situations related to impacts on water use and quality by reference to rainfed and irrigated systems for corn and soybean production in temperate regions. These authors concluded that soybean cultivation was more susceptible to ecotoxicity and has a greater environmental impact than corn production.

Analysis of the EPI (2022) shows that accumulated emissions in the form of air pollution, effluent flows into waterways, mismanaged waste, chemical releases and greenhouse gases harm human health and ecosystems. To counter these negative impacts, many countries have enacted policies to significantly reduce their greenhouse gas emissions. In this respect, Denmark and the United Kingdom plan to reach greenhouse gas neutrality by 2050; however, China, India and Russia are still heading in the wrong direction.

Best practices for environmental sustainability include sustainability benchmarking and information disclosure at various levels of government (Alcaraz-Quiles et al., 2014), to facilitate meaningful international comparisons and long-term monitoring (Del Campo et al. 2021; Gallego-Álvarez et al., 2018). The adequate availability of information enables policymakers and others to assemble metrics and tools to gauge the adequacy of national policies, thus providing a mechanism for holding governments to account (EPI, 2022;

CEPALSTAT, 2022; World Bank, 2022). Stakeholder concerns in the development of sustainability policies led to the adoption of the UN Framework Convention on Climate Change (UNFCCC, 2021), as an international initiative to collaborate for the greater good. Policymakers in the European Union have observed that policies favoring environmental sustainability can also produce competitive advantages for their proponents (Boasson & Wettestad, 2016), and promote the legislation of the Inflation Reduction Act (IRA), which aims to promote renewable energy and reduce dependence on fossil fuels in the global economy (Ma et al., 2024)

Thus, indicators of environmental sustainability can function as a social tool, enabling stakeholders to identify and analyze differences in environmental performance assessments by policy category, objective and country. Porter (1991) suggested this would generate a win-win situation, in the sense that environmental policies benefit the environment and at the same time enhance competitiveness. These outcomes are evidently much sought after by policymakers, in view of the growing number of green "new deals" and "net zero" carbon emission pledges being made at the national level. However, there is a marked gap between the environmental policy data needed and the real supply of reliable indicators and indices (Herman & Shenk, 2021).

Most South American countries have made significant recent progress in regulating environmental sustainability (see Appendix A), with particular reference to critical water issues, to protect and manage this increasingly scarce resource. In many cases, governments are making increasing use of visioning, back casting and adaptive environmental management to anticipate and respond to change, complexity and uncertainty, whilst pursuing effective implementation, monitoring and evaluation (Mitchell, 2013). Furthermore, many have ratified international agreements in this respect, such as the Paris Agreement on Climate Change (except for Chile and Ecuador) and have established agencies to protect biodiversity and protected areas and to prosecute cases of criminal responsibility. However, climate change remains uncontrollable, since factors such as global warming, excessive greenhouse gas emissions, and the use of fossil fuels (Kiehbadroudinezhad et al., 2024), losses of biodiversity and improper waste management will continue to prevail. Notwithstanding, and as highlighted by Paredes-Beltrán (2021), EPI (2022), Del Campo et al. (2021) and Miranda et al. (2020), the countries of South America are well aware of the extreme gravity of the environmental problems facing the region. Few studies have assessed and compared regional trends in environmental sustainability in South America. Major barriers to this type of research include, weak regional monitoring, limited coverage, varied measurement techniques, and complex access to air quality data (Clean Air Institute, 2013).

DATA AND METHODOLOGY

Sample Location and Availability

This paper aims to evaluate the environmental sustainability performance of twelve South American countries (Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay and Venezuela), considering data published in 2019 according to data published in 2019, the CEPALSTAT database (see Table 1) and survey data published by the ECLAC, one of five regional commissions established by the United Nations (UN) to contribute to economic development (Martínez, 2019), and the similarities and differences can be observed among the indicator practices in these countries of two statistical methods, Principal Component Analysis (PCA) and Cluster Analysis (CA).

The study data reflect the similarities and disparities among the countries in terms of the following dimensions: production of secondary energy and change in energy intensity, proportion of protected marine areas for the preservation of biological diversity, contribution to the persistence of marine biodiversity, proportion of protected areas to preserve terrestrial and marine biodiversity, global warming, pollution and overexploitation of the sea.

Principal Component Analysis (PCA)

In this study, indicators of environmental sustainability are determined by means of principal component analysis (PCA), a multivariate technique which identifies latent variables that while not directly observable can be inferred (via a mathematical model) from other variables that are observable and can be measured directly. With this approach, the degree of environmental responsibility and sustainability (of an individual, organization, community or country) can be quantified.

The increasing demand by countries for information on the status of their natural resources and marine biodiversity has led to the creation of databases and the development of methodological and statistical capacity to produce reliable indicators of the results of the environmental sustainability policies applied by countries or regions. Such actions produce long-term effects, justifying our use of multivariate techniques in their analysis. This study of environmental sustainability and its correlation with supporting statistical data was conducted in order to quantify sustainability in terms of environmental indicators. Moreover, the development of an optimal system of indicators helps to explain the dynamics of environmental sustainability and the goals achieved.

The multidimensional approach taken to the system of environmental sustainability indicators reflects the complex reality of national systems and of each of the components involved in the transformation of urban and rural productive activity. Each dimension of the system has its own characteristics; it both constrains and is conditioned by the other dimensions (Sepúlveda et al., 2002). To achieve sustained growth and development, institutional actors and economic agents must be aware of current stocks of renewable natural resources and the environment in which they operate and be capable of managing them from a long-term perspective.

In our analysis, the measurement of environmental sustainability is associated with the concept of *construct*, as a means of understanding the data, goals and thresholds of sustainability with a high level of abstraction. Constructs are subjective variables designed to measure the changes implicit in a given phenomenon or process. They are objectively verifiable and replicable, and are considered analytical tools that facilitate the measurement of the hidden changes within a system that manifest themselves in observable variables. Principal Component Analysis (PCA) is a technique from statistics for simplifying a data set. It was developed by Pearson (1901) and Hotelling (1933).

In our study, in order to avoid problems arising from the use of different measurement scales, all variables are standardized by transformation into z-scores with a mean of 0 and a standard deviation of 1. This approach is used to configure the correlations present in a set of observed variables. Appropriate environmental sustainability constructs are derived by means of a multivariate analytical approach (Glave & Escobal, 1995), i.e., principal component analysis (Pearson, 1901; Hotelling, 1933, 1936). The first such approach employed is that of an unsupervised learning algorithm, which uses multivariate statistical techniques to reduce the original seventeen variables to six, the minimum number that reflects the variability in the data set with minimal loss of information (see tables 1 and 2).

Cluster Analysis (CA)

Cluster analysis is well established and can be applied as a hierarchical method or as a k-means method. The hierarchical method divides a set of individuals (in this case, countries) into smaller groups, so that those belonging to the same set are very similar to each other, but very different from those assigned to other groups −i.e., there is inter-group homogeneity and intra-group heterogeneity− (Kaufman & Rousseeuw, 2009).

In our study, cluster analysis makes it possible to obtain a typology of countries such that each cluster corresponds to certain patterns of behavior and performance in terms of environmental sustainability. Among other outcomes, this analysis identifies the countries with best practices in terms of the environmental indicators considered and shows how they have evolved over time.

The results obtained could facilitate the benchmarking of environmental practices and hence foster improvement. Based on the indicators described, we identify the groups of countries that present similar characteristics and those that behave as outliers and highlight their most important features and their role in the South American context.

Furthermore, as the study variables are cross-sectional (referring to 2019), we also considered model-based clustering. Finally, the fact that only twelve countries were included in the analysis means that the complexity related to large databases, which is one of the main drawbacks of hierarchical methods (Aghabozorgi et al., 2015), was not experienced.

In the multivariate methodology applied in this study, eigenvectors and eigenvalues are extracted from the correlation matrix. From the eigenvalues, we obtain the proportion of variance explained by each component of the total variance present in the data set of interest. Since the sum of the eigenvalues quantifies the total variance explained by the factors, we seek to maximize this proportion. In this selection process, it is important to consider only those components that contribute most to explaining the total variance. A criterion commonly adopted is that at least 80% of the total variance should be explained, such that the significant reduction obtained in the dimensionality of the original data set produces the least possible loss of information.

The results thus obtained are then evaluated with the eigenvectors, to determine how the variables behave in each of the different components, and to obtain elements for their definition. An important consideration is that the lower the eigenvalues the more difficult it becomes to define the components on the basis of the eigenvectors, i.e., the less the component explains the variability of the data. Having identified the indicators that impact on environmental sustainability, we now make further use of multivariate statistics (cluster analysis) to generate country profiles according to the environmental practices observed.

Under the clustering method applied, we first grouped the two closest elements and then successively combined pairs of elements, gradually forming larger groups until all the elements were incorporated. This process can be interrupted at any level of the clustering “tree” created, thus enabling the desired number of groups to be obtained directly. In this process, it is useful to calculate a metric of cluster quality (minimizing the distance between data elements in the same cluster and maximizing the distance with respect to the other clusters) to determine an appropriate cutoff level.

In this study, hierarchical cluster analysis was applied, using Ward's method with squared Euclidean distances, which from practical experience produces the best results in this type of situation (Ward, 1963). A formal, rigorous description of these techniques can be found in Everitt et al. (2011), Hair et al. (2009) and Kaufman and Rousseeuw (2009). See also Aghabozorgi et al. (2015) for an exhaustive review of clustering time series.

The above-described cluster analysis enables us to obtain the proximity matrix from the data matrix X of order *nxp* and to construct the distance matrix S of order *nxn*, where each coefficient of S, *sij*, indicates the distance between the countries of interest according to the latent variables considered, such that each value of a dissimilarity coefficient for cases *i* and *j* measures the degree of dissimilarity/distance of the individuals. This matrix is symmetric, given that *sij* = *sji*.

Table 1. Sustainable environmental indicators

No.	Abbreviation	Name	Description	Source
			Atmosphere climate and weather conditions	
1	ATV	Average Temperature Variation	This indicator contains data on the observed variations in the average surface temperature by country, with annual update.	CEPALSTAT
			Geological and geographical information	
2	CAT	Country Area (Total)	This indicator shows the total land area and inland waters of a country. Total area: includes areas occupied by inland water bodies (main rivers, lakes and reserves) and the land area of the country *divided Population* Excludes territorial waters or territorial sea.	CEPALSTAT
			Land cover	
3	PPAMA	Proportion of Protected Areas in relation to Marine Areas	This indicator shows temporal trends in the average percentage of each important site for marine biodiversity (i.e. those that contribute significantly to the global persistence of biodiversity) that is covered by designated protected areas.	CEPALSTAT
4	PTDPA	Proportion of important places for Terrestrial Diversity that constitute Protected Areas	This indicator shows temporal trends in the average percentage of each important site for terrestrial biodiversity (i.e. those that contribute significantly to the global persistence of biodiversity) that is covered by designated protected areas.	CEPALSTAT
5	PMDPA	Proportion of important places for Marine Biodiversity that constitute Protected Areas	This indicator shows temporal trends in the average percentage of each important site for marine biodiversity (i.e. those that contribute significantly to the global persistence of biodiversity) that is covered by designated protected areas.	CEPALSTAT
6	AMPA	Area of Marine Protected Areas	This indicator presents the area of marine protected zones in a country, dedicated to preserving biological diversity and associated resources. These areas, including intertidal and subtidal zones, are legally designated or protected by effective means to safeguard their environmental, historical, and cultural characteristics.	CEPALSTAT
7	PTMPA	Proportion of Terrestrial and Marine Protected Areas	This indicator presents information on the surface of total protected areas (terrestrial and marine), with respect to the total territorial area (terrestrial and marine) of a country.	CEPALSTAT
8	PMPA	Proportion of Marine Protected Areas	This indicator presents information on the area of marine protected areas, with respect to the marine territorial area of a country.	CEPALSTAT

Continuation Table 1

			Air quality	
9	CLFPM	Concentration Level of Fine Particulate Matter (PM25)	This indicator presents the annual average concentration of PM2.5 [µg/m3] in Latin America and the Caribbean. PM2.5 particles, which penetrate deep into the respiratory tract, pose health risks, increasing mortality from respiratory infections, lung cancer, and cardiovascular diseases. WHO's Air Quality Guidelines aim to reduce PM2.5 to 10 µg/m3 annually.	CEPALSTAT
			Energy resources - energy production renewable and non-renewable resources	
10	PCERNRE	Rate of change in the energy intensity of GDP (primary energy supply/ GDP at constant prices in 2010 dollars)	This indicator measures the annual percentage change in energy intensity of GDP (Primary energy supply/GDP at constant 2010 dollars). A positive rate shows increased energy intensity, indicating reduced energy efficiency, while a negative rate shows reduced energy intensity, indicating improved efficiency. It supports monitoring SDG 7.3 on energy efficiency.	CEPALSTAT
11	EP_E	Energy Production: Electricity, Secondary Energy	It corresponds to the different energy products that come from the transformation of primary energy products; their destination is the various consumption sectors and/or other transformation centers (as in the case of gasoline, electricity and liquefied gas, among others).	CEPALSTAT
12	EP_SE	Energy Production: Secondary Energy	It corresponds to the different energy products that come from the Electricity, Liquefied gas, Gasoline/ alcohol, Kerosene and turbo, Diesel oil, Fuel oil, Coke, Charcoal , Gases, Other secondary, Non-energy.	CEPALSTAT
13	ECS	Energy Consumption (secondary)	This indicator presents information regarding total, primary and secondary energy consumption in a country. Secondary energy consumption refers to production plus imports, minus exports, plus changes in reserves and minus distribution losses of all secondary energy products (which are the result of the transformation of products primary energy sources).	CEPALSTAT
14	RPPES	Renewable Proportion of Primary Energy Supply	This indicator measures the proportion of a country's primary energy supply derived from renewable sources. Renewable primary energy comes from non-fossil resources with short or continuous formation periods, ensuring sustainable availability under rational exploitation regimes without decreasing over time.	CEPALSTAT
			Biological resources	
15	CFP_T	Capture fisheries Production_Total	This indicator presents information on the total volume of capture of the following species: crustaceans, molluscs, freshwater and marine fish, aquatic plants, among the main ones. Both in continental and marine waters.	CEPALSTAT
16	AP_T	Aquaculture Production_Total	This indicator presents information on the volume of total aquaculture production, which includes freshwater and marine aquaculture. Aquaculture is the breeding and cultivation of aquatic organisms, be they fish, molluscs, crustaceans or aquatic plants. The total aquaculture production volume covers freshwater aquaculture and marine aquaculture.	CEPALSTAT
			Crops	
17	IFU	Intensity of Fertilizer Use	This indicator refers to the amount of fertilizer used by the countries. Fertilizer: Organic and inorganic substances whose chemical elements allow to stimulate the development of plants and improve soil fertility.	CEPALSTAT

Source: own elaboration

The distance matrix was obtained using the "average link between groups" clustering method and taking the squared Euclidean distance as the clustering measure (see Note 1). In statistical analysis, a similarity measure or function is a real-valued function that quantifies the similarity between two objects, even though there is no single definition of similarity.

RESULTS

Principal Components Analysis (PCA)

From the Kaiser criterion of eigenvalues greater than one and considering the slopes of the sedimentation plot (see Figure 1), we find that 91,7% of the total variance can be explained by six principal components, which represents a significant percentage of the variability present in the data set under study (see Table 4). The following principal components were selected:

- PC1: Secondary energy production and change in energy intensity.
- PC2: The proportion of marine protected areas for the conservation of biological diversity.
- PC3: The contribution to the persistence of marine biodiversity.
- PC4: Proportion of areas protected to conserve terrestrial and marine biodiversity.
- PC5: The impact of global warming.
- PC6: Measures taken to counter pollution and overexploitation of the sea.

In terms of environmental sustainability, these indicators relate to the conservation of natural resources and biodiversity and reflect an awareness of the finite nature of these resources, of the fragility of the physical environment and of how it is affected by human activities.

This analytical perspective is related to biodiversity, climate, pollution, energy, and the efficient use of natural resources. To properly interpret the elements considered, we must examine the correlations obtained between the variables and the PCs to determine the strength of the relationship between them (Table 3). In this regard, the following results were obtained.

PC1 is significantly correlated with secondary energy production and change in energy intensity (>90%).

PC2 incorporates variables related to marine protected areas and the variety of marine life (correlations >0.9). The relationship is positive, meaning that increasing protection for marine areas would enhance marine biodiversity.

PC3 reflects the severe effects produced on the marine ecosystem by the aquaculture industry and the intensive use of fertilizers in agriculture. Among other criticisms, aquaculture is associated with the destruction of mangroves and with a negative environmental impact on receptor ecosystems, due to the excessive consumption of resources, the transformation of the habitat and the generation of the final product. The intensive use of fertilizers generates an excess of nutrients that subsequently contaminate surface water and groundwater. This component, therefore, reflects the need to protect the marine environment.

PC4 includes terrestrial biodiversity preservation practices, the generation of energy from renewable sources, and the total percentage of protected areas. This construct reflects practices of terrestrial and marine biodiversity protection.

PC5 concerns the variations in average temperature by area and in the total area of land and inland water. Thus, this component captures the impact of global warming.

Finally, PC6 combines the production of fish (including crustaceans and mollusks) with the concentration of air pollution particles. This component is an indicator of pollution and overexploitation of the sea.

Table 2. South America: principal components (PC) or constructs

Factor	Significant factor-variable correlation	Description	Label
Factor 1	EP_SE 2019. Secondary Energy Production EP_E 2019. Energy Production Electricity PCERNRE 2019. Rate of Change in the Energy Intensity of GDP. ECS 2019. Secondary Energy Consumption	Secondary energy production (kerosene, alcohol, coke, others). Electricity production (transformation of primary energy products for sectoral consumption and transformation centers). Rate of change in energy intensity of GDP (primary energy supply/GPD at constant prices in 2010 dollars). Secondary energy consumption (shows the total secondary energy consumption. Production + imports - exports + change in energy reserves - distribution of secondary energy loss).	Secondary energy production and energy intensity
Factor 2	PMPA 2019. Proportion of Marine Protected Areas AMPA 2019. Marine Protected Areas PMDPA 2019. Proportion of Important Places for Marine Biodiversity	Ratio of marine protected areas to total marine area owned by each country Marine protected areas (protection and maintenance of biological diversity) Proportion of sites important for marine biodiversity (shows the time trend of the average percentage of each site relevant to marine diversity = shows the contribution of protected sites to the overall persistence of biodiversity)	Proportion of marine protected areas for the preservation of biological diversity
Factor 3	AP_T 2019. Aquaculture Production Total PPAMA 2019. Proportion of Protected Areas in Relation to Marine Areas IFU 2019. Intensity of Fertilizer Use	Total aquaculture production (breeding and culture of aquatic organisms = fish, mollusks, crustaceans and aquatic plants). Proportion of protected areas in relation to a country's marine area (contribution to global persistence of biodiversity). Quantity of fertilizer used by countries	Contributing to the persistence of marine biodiversity
Factor 4	PTDPA 2019. Proportion of Important Places for Terrestrial Diversity that Constitute Protected Areas RPPES 2019. Renewable Proportion of Primary Energy Supply PTMPA 2019. Proportion of Terrestrial and Marine Protected Areas	Proportion or average percentage of areas protected for terrestrial biodiversity. Ratio of renewable primary energy supply (proportion of primary energy supply that comes from renewable sources, with respect to the primary energy supply that each country possesses. Ratio of terrestrial and marine protected areas (total area of terrestrial protected areas) to total land area (land and sea).	Proportion of protected areas to preserve terrestrial and marine biodiversity
Factor 5	ATV 2019. Average Temperature Variation CAT 2019. Country Area Total	Displays the observed variations in average temperature by country, as annual data. Shows the total area of land and inland water of the country (rivers, lakes, reservoirs, swamps, etc.).	Global warming
Factor 6	CFP_T 2019. Capture Fisheries Production. Total CLFPM 2019. Concentration Level of Fine Particulate Matter	Capture fisheries production. Total (catch volume of crustaceans, mollusks, freshwater and marine fish, aquatic plants, etc.). Concentration level of fine particulate matter less than 2.5 microns in diameter. Air pollution.	Pollution and overexploitation of the sea

Source: own elaboration

Our analysis revealed moderate to strong correlations between the four indicators of environmental sustainability and PC1 (secondary energy production and change in energy intensity). Positive correlations were also observed between three indicators and PC2 (proportion of marine protected areas for the preservation of biological diversity) and PC3 (Contributing to the persistence of marine biodiversity) and PC4 (proportion of areas protected to conserve terrestrial and marine biodiversity).

Conversely, the correlation with renewable proportion of primary energy supply was negative. Correlations were strong with average temperature variation and country area (total) and with PC5 (global warming), while the correlations between both fish capture production and concentration of fine particulate matter and PC6 were very high (see Table 3).

Table 3. Rotated component matrix (a)

	Component					
	1	2	3	4	5	6
Score Z: EP_SE 2019	,974					
Score Z: EP_E 2019	,974					
Score Z: PCERNRE 2019	,967					
Score Z: ECS 2019	,966					
Score Z: PMPA 2019		,957				
Score Z: AMPA 2019		,936				
Score Z: PMDPA 2019		,783				
Score Z: AP_T 2019			,904			
Score Z: PPAMA 2019			,881			
Score Z: IFU 2019			,807			
Score Z: PTDPA 2019				,923		
Score Z: RPPES 2019				-,790		
Score Z: PTMPA 2019				,762		
Score Z: ATV 2019					,845	
Score Z: 2019					,838	
Score Z: CFP_T 2019						,890
Score Z: CLFPM 2019						,730

Extraction method: principal component analysis.
Rotation method: Varimax with Kaiser normalization.
(a). The rotation has converged in 7 iterations.

Source: own elaboration

Table 4 and Figure 1 show the seventeen components with eigenvalues (coefficients applied to eigenvectors that give the vectors their length or magnitude) through the extraction method, i.e., principal component analysis (PCA).

Larger eigenvalues correlate with more important directions.

Table 4. Total variance explained

Component	Initial eigenvalues			Sums of squared extraction charges			Sums of loads squared by rotation		
	Total	% variance	% accumulated	Total	% variance	% accumulated	Total	% variance	% accumulated
1	5,961	35,066	35,066	5,961	35,066	35,066	4,586	26,977	26,977
2	2,870	16,885	51,950	2,870	16,885	51,950	2,707	15,924	42,901
3	2,615	15,385	67,335	2,615	15,385	67,335	2,688	15,810	58,711
4	1,834	10,786	78,121	1,834	10,786	78,121	2,258	13,285	71,996
5	1,262	7,423	85,544	1,262	7,423	85,544	1,775	10,440	82,436
6	1,051	6,182	91,726	1,051	6,182	91,726	1,579	9,290	91,726
7	,723	4,251	95,977						
8	,435	2,560	98,537						
9	,174	1,022	99,559						
10	,048	,281	99,840						
11	,027	,160	100,000						
12	7,857E-16	4,622E-15	100,000						
13	1,151E-16	6,771E-16	100,000						
14	2,837E-17	1,669E-16	100,000						
15	-1,241E-16	-7,300E-16	100,000						
16	-2,363E-16	-1,390E-15	100,000						
17	-4,844E-16	-2,849E-15	100,000						

Extraction method: principal component analysis.

Source: own elaboration

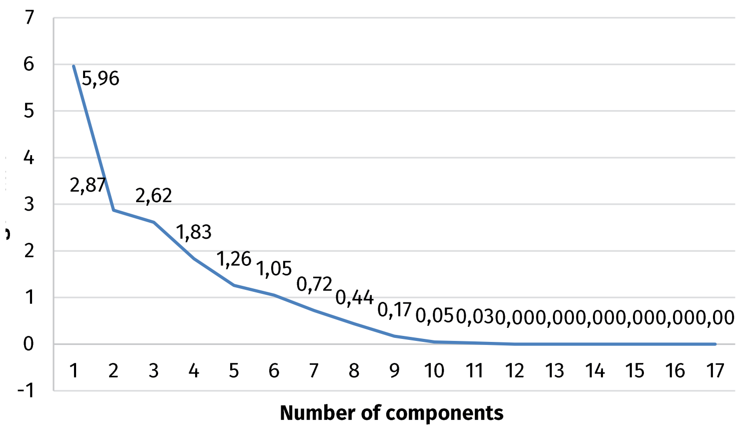

Figure 1. Sedimentation

Finally, the total variability is captured by the projections of the data onto the first principal components, so that the first component is a direction that maximizes the variance of the data, and that the i-th component can be considered as a direction orthogonal to the first i -1 principal components that maximizes the variance of the projected data.

Cluster Analysis (CA)

The distance or similarity matrix is examined in order to determine the true structure of the data under study, since many of the coefficients reported may be related. Consequently, the concordance of the results may reflect the type of grouping structure being sought, assuming that scores will be lower when these groups are more similar, and that higher scores will reflect dissimilarity. The distance matrix, thus, functions as a quantitative tool to evaluate the similarity of countries in terms of their environmental practices, enabling us to associate countries with comparable characteristics.

In the present study, the squared Euclidean distance was calculated to obtain the coefficients and hence the required grouping structure. The results of this calculation are shown in Table 5. The countries that present similarities in terms of their long-term environmental practices and sustainability are Venezuela and Colombia (0.497), Paraguay and Guyana (0.531), Suriname and Colombia (3.442), Guyana and Argentina (3.469), Venezuela and Suriname (3.670) and Bolivia and Argentina (3.705).

Table 5. Proximity matrix

Case	Squared Euclidean Distance											
	1:ARG	2:BOL	3:BR	4:CL	5:CO	6:EC	7:GUY	8:PAR	9:PE	10:SUR	11:URY	12:VEN
1:ARG	,000											
2:BOL	3,705	,000										
3:BR	26,466	29,049	,000									
4:CL	22,298	34,173	18,967	,000								
5:CO	4,188	5,193	13,179	18,717	,000							
6:EC	24,594	27,224	15,808	19,600	11,158	,000						
7:GUY	3,469	7,210	31,019	30,759	10,556	40,031	,000					
8:PAR	4,114	10,177	28,031	26,390	10,929	39,080	0,531	,000				
9:PE	7,063	12,741	18,662	16,166	6,681	17,170	9,092	8,326	,000			
10:SUR	12,924	7,646	12,962	27,609	3,442	12,150	20,167	21,910	14,519	,000		
11:URY	4,860	16,704	31,918	19,399	12,172	33,438	6,440	4,420	9,808	27,806	,000	
12:VEN	4,181	3,974	16,473	23,867	0,497	12,198	10,347	11,474	6,665	3,670	13,651	,000

Source: Own elaboration

Ecuador, Brazil and Chile present very high similarity coefficients (above two digits), which indicates that their environmental sustainability-related practices differ significantly, both among themselves and with the other countries analyzed.
This disparity is reflected in the biodiversity indicators published by international organizations. Among these three countries, Ecuador presents greater degradation of biodiversity than Chile and Brazil.
In the next phase of the analysis, we construct a hierarchical classification of the twelve countries, in which the individuals are not simultaneously partitioned into clusters; instead, successive partitions are made at different levels of aggregation, following a priority or hierarchy, becoming progressively less homogeneous as the groups become larger. This successive partitioning is carried out by combining the six latent indicators identified by principal component analysis. The outcome of this process is a dendrogram showing the degree of clustering of the countries according to their similarities and differences regarding environmental sustainability practices.

To perform the above partitioning, it is first necessary to determine the number of clusters that reflect the profiles of the countries under study. This decision-making process is usually represented by an iterative algorithm and by the distances at which countries should be grouped according to their environmental profiles.

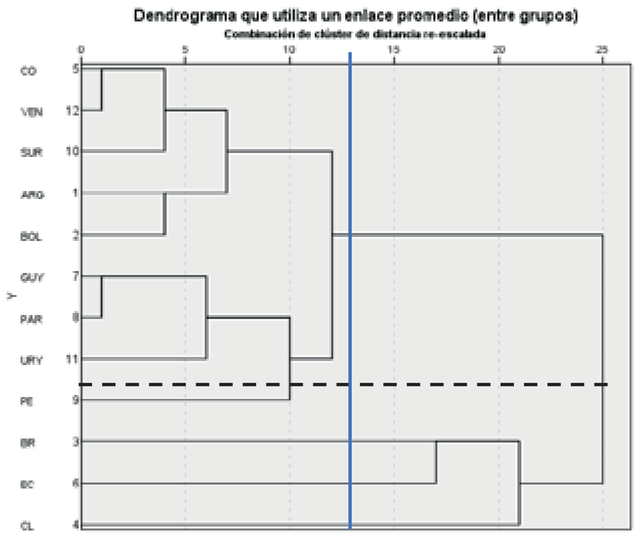

Figure 2. Clustering dendogram in South American countries

Source: own elaboration

Figure 2 shows that in this dendrogram, the initial jumps in terms of distance are small, while later jumps are more widely spaced. The cutoff point taken is the point at which sharp jumps or large distances begin to occur.

The dendogram shows that five clusters are located below the continuous line (see Figure 2). Analysis of the successive increases in the distances between the clusters (jumps on the vertical axis of the values for the intergroup sums of squares values) shows that a reasonable choice would be the five-cluster solution at a distance of ten rescaled points. This is because when more than five clusters are considered, the jumps in terms of the inter-group distances are very significant. Accordingly, the twelve countries analyzed in this study are grouped into five clusters:

Cluster 1 – Colombia, Venezuela,
Suriname, Argentina and Bolivia
Cluster 2 – Guyana, Paraguay, Uruguay and Peru
Cluster 3 – Brazil
Cluster 4 – Ecuador
Cluster 5 – Chile

In the following, we detail the characteristics of each cluster.

Cluster 1. Colombia, Venezuela, Suriname, Argentina and Bolivia. These countries employ similar environmental practices, moving towards low-emission and climate change resilient economies, and promoting innovative solutions in key sectors such as renewable energy, agriculture, electromobility, financial institutions and biodiversity. Among related projects, Argentina has launched the program "Strengthening governance to implement land degradation neutrality objectives through sustainable management of forests and agricultural systems", financed by the Global Environment Facility (GEF). The aim of this program is to reduce climate vulnerability, improve land productivity and protect social fairness and environmental quality in agroecosystems, in three river basins in Argentina. Other initiatives include the joint Argentina-Bolivia project "Integrated management of water resources in the Bermejo River basin", financed by GEF, aimed at achieving the integrated planning and management of the Bermejo River basin and the sustainable use of natural resources. In Colombia, the project "Energy efficiency for the transition to carbon neutral cities" seeks to reduce CO2 emissions by increasing energy efficiency in the construction sector in the regions of Barranquilla, Montería and Pasto, via actions addressing the different stages of the life cycle of buildings and interventions in public spaces, focusing on three key components: energy efficiency in buildings and public spaces; the management of sustainable projects; and the dissemination and management of knowledge related to the environment and global warming.

Cluster 2. Guyana, Paraguay, Uruguay and Peru. These countries all present environmental problems related to the overexploitation of water resources, the emission of greenhouse gases by extensive livestock farming, and the loss of biodiversity associated with agriculture due to the intensive use of chemical fertilizers and artificial farming methods and the inadequate treatment of industrial waste. These countries, hence, feature weak environmental performance and poor protection of marine and terrestrial areas.

Cluster 3. Brazil. According to the System for Estimating Greenhouse Gas Emissions (SEEG, 2021) Municipalities, part of the Climate Observatory initiative, and the online journal Expansion, Brazil is one of the worst performers among 184 countries in terms of CO2 emissions. This situation is aggravated by the uncontrolled burn-off of the rainforests, which pollutes the air breathed by millions of people and impacts on human health throughout the Amazon region, according to the Amazon Environmental Research Institute (IPAM, 2021).

Cluster 4. Ecuador. The main environmental problems facing Ecuador are deforestation, agribusiness, hydroelectric power generation, mining, and weak environmental institutions. However, the authorities have pledged to reform the energy matrix, reduce deforestation, and promote responsible, sustainable consumption. In short, this country aims to improve its environmental performance, although it is currently failing to provide adequate protection for marine and terrestrial biodiversity.

Cluster 5. Chile. Chile's main environmental problems are air pollution, water scarcity and pollution, soil loss and contamination, noise pollution, inadequate solid waste management and the loss of biodiversity. However, Chile has strengthened its environmental institutions on the basis of a multisectoral environmental coordination model. It has also stepped up its environmental initiatives in the areas of air, water, waste and biodiversity management, using innovative instruments innovative instruments (e.g. trade) and successful reforms (e.g. water services).

Figure 3 illustrates the significant heterogeneity in environmental sustainability in South America, and the performance of the countries in each of the clusters identified.

Table 6. Conglomeration history

Stage	Combined cluster		Coefficients	First appearance of the stage cluster		Next stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	5	12	,497	0	0	3
2	7	8	,531	0	0	5
3	5	10	3,556	1	0	6
4	1	2	3,705	0	0	6
5	7	11	5,430	2	0	7
6	1	5	6,351	4	3	8
7	7	9	9,075	5	0	8
8	1	7	11,661	6	7	11
9	3	6	15,808	0	0	10
10	3	4	19,284	9	0	11
11	1	3	23,859	8	10	0

Source: own elaboration

Figure 3. Environmental sustainability in 2019

Source: own elaboration

In every case, complex situations must be addressed. However, all twelve countries face certain problems that are common to all. These include deforestation, the intensive use of fertilizers in agriculture, the greenhouse effect, the pollution associated with extensive livestock farming, inadequate management of solid waste and an enormous loss of biodiversity.

The efforts of these countries to develop a sustainable economic and social policies consistent with environmental objectives are reflected in the development of appropriate regulations and in their efforts to generate quantitative indicators to monitor progress in this context.

DISCUSSION

Historically, models of national growth and development have not been linked to environmental objectives but have been used to identify the spatial distribution of economic activities, the territorial concentration of the population, the location and degree of growth of urban centers, and the types of links between certain territorial units and the rest of the national territory. However, this type of territorial distribution takes little account of its environmental consequences, especially in the medium and long term.

In practical terms, this phenomenon has generated a process of spatial differentiation in which each country or region acquires specific productive, economic and socio-political characteristics, as a functional component of a complex national development matrix, with limited environmental objectives.

The spatial differentiation thus created and the types of geographic connections established are evident in three main ways:

- A geographic concentration of economic activities and population in certain territorial units and in urban centers that tend to become megalopolises.
- The centralization in these territorial units of the institutional system responsible for decision making.
- Extreme disparities between the living conditions of the population located in these territorial units and those living elsewhere.

These characteristics accentuate environmental problems and produce disparities in how current models of growth address questions such as global warming and the loss of biodiversity.

In the present study, indicators of environmental problems are used to group countries with similar patterns of behavior in order to identify the main characteristics of the configuration of clusters and the role they play in South America.

All twelve South American countries considered in this study have signed and ratified various international treaties and conventions on climate change biodiversity and ecosystems, sustainable development, ocean protection and the management of waste and hazardous chemicals (see Note 2 and Appendix B).

The study's findings highlight the uneven progress made by these countries in addressing environmental problems. In this respect, the 2023 Regional Conference on South-South Cooperation in Latin America and the Caribbean called for economic integration and partnerships for sustainable growth, with a view to fulfilling the United Nations 2030 Agenda.

The Peruvian Agency for International Cooperation (APCI) was created in 2002, the Ecuadorian Agency for International Cooperation (AGECI) in 2007 (in July 2010, its name was changed to that of the Technical Secretariat for International Cooperation), the Colombian Presidential Agency for Cooperation (APC) in 2011, the Mexican Agency for International Development Cooperation (AMEXCID) in 2011, and the Uruguayan Agency for International Cooperation (UCI) in 2011 (Rivero & Xalma, 2019). In the remaining LAC countries, development cooperation policies, programs and activities have been strengthened with the creation of new offices or departments within one or more government ministries (see Table 7).

Table 7. Latin America and the Caribbean: institutional framework for development cooperation

	Institution			
		Within the Ministry of Foreign Affairs		
	Cooperation agencies	Solelye within the Ministry of Foreign Affairs	Within the Ministry of Foreign Affairs and another ministry or department	Within another ministry or government department
Latin America	Brazil, Chile, Colombia[a], Ecuador[a], El Salvador[a], Mexico, Peru and Uruguay[a].	Argentina, Costa Rica, Honduras, Panama, Paraguay and Venezuela (Bolivarian Republic of).	Guatemala and Nicaragua.	Bolivia (Plurinational State of), Cuba.

In Colombia, Ecuador, El Salvador and Uruguay, in addition to the cooperation agency, there is a department (vice-ministry or directorate) for international cooperation within the Ministry of Foreign Affairs.

Source: Oviedo (2021).

In line with the findings obtained by other authors, there is currently a high level of environmental concern in South America. However, some countries have shown to be more concerned about climate change; these countries include Argentina, Chile and Brazil (Gallego-Álvarez et al., 2018). Chile is promoting the development of green hydrogen, while Brazil is a leader in renewable energy, with hydroelectric power. According to Darré et al. (2019) Uruguay's agricultural land increased by 138%, led by the soybean expansion (1,140,000 ha), making it one of the world's top six global exporters in the world. However, this land is not exempt from various environmental problems such as soil degradation, water pollution, deforestation, and loss of biodiversity.

The 2022 Environment Performance Index (EPI) shows that the highest scoring countries in the region are Chile and Suriname. Many countries with mid-range scores include Brazil, Colombia, Argentina, Paraguay, Bolivia, and Peru. At the other end of the Index, countries with low scores include Guyana and Uruguay, which have made little significant progress. There is a very high correlation between a country's wealth and its EPI score, so the environmental challenges vary according to a country's wealth and level of development of the countries. Ideas about environmental sustainability are therefore likely to reinforce already existing institutional and discursive settings (Crabb & Leroy, 2008); Alcaraz-Quiles et al., 2014; Olafsson et al., 2014; Boasson & Wettestad, 2016; Miranda et al., 2020).

CONCLUSIONS

This paper aims to evaluate the environmental sustainability performance of twelve South American countries, considering data published in 2019. Indicators of environmental sustainability highlight the evaluation of each country in this regard, and can be used to promote benchmarking. Multivariate statistical techniques are used to group the countries into five homogeneous clusters. The results obtained show that there are clear differences between these countries in terms of environmental sustainability, but that overall performance has improved in each case.

In relation to the production and secondary consumption of energy (PC1), Brazil, Argentina and Venezuela recorded progressive growth in indicators 10, 11, 12 and 13 (see Table 1). Brazil recorded the highest production capacity of renewable energy. By contrast, the production capacity of Guyana and Suriname has fallen in recent years due to their increased use of fossil fuels, although Suriname has received IDB assistance in energy reform projects (regarding institutional and regulatory reform, digitalization, sustainable infrastructure, energy access and renewable energies) to promote clean energy.

Ecuador, Peru and Brazil report the highest proportions of marine protected areas (Indicator 2), while neither Bolivia nor Paraguay have any such protected area. In absolute terms, Chile and Colombia have the largest Marine Protected Areas. The Nazca-Desventuradas Marine Park (Chile) is the largest single marine protected area in the Americas. According to Indicator 5 (Proportion of important places for marine biodiversity that constitute a protected area), Suriname, Ecuador, Brazil and Colombia each have a significant number of these locations, but Bolivia, Guyana and Paraguay have none.

Peru, Chile, Ecuador and Brazil score highly for total aquaculture production (Indicator 3), in contrast to Suriname, Uruguay and Paraguay. Chile, Brazil and Colombia each have a significant proportion of protected areas in relation to marine areas (Indicator 3), while Bolivia and Paraguay have none. The lowest levels for intensity of fertilizer use (Indicator 17) are recorded for Bolivia, Guyana, Peru and Suriname, and the highest values, for Chile, Brazil, Uruguay and Ecuador.

Venezuela, Suriname, and Bolivia record the highest values, and Guyana and Uruguay, the lowest ones, for the proportion of important places for terrestrial diversity that constitute protected areas (Indicator 4). Paraguay, Guyana and Suriname score well for hydropower, solar, wind, geothermal, bioenergy, wave and tidal energy resources (Indicator 14), unlike Venezuela, Argentina and Bolivia. The leading countries for the proportion of terrestrial and marine protected areas (Indicator 7) are Venezuela, Bolivia and Brazil, while Argentina, Guyana and Chile score poorly in this respect.

The strongest average temperature variations (Indicator 1) are presented by Paraguay, Suriname, Brazil, Colombia, Venezuela and Ecuador, although in general the entire continent has experienced rising temperatures over the past fifteen years. Brazil, Argentina and Peru are the largest in terms of CAT (total surface area, including inland waters), while Suriname, Uruguay, Guyana and Ecuador are the lowest ranking in this regard.

Among the indicators regarding Factor 6, the highest values for total fisheries capture production (Indicator 15) are reported by Peru, Chile and Argentina, at levels that have not significantly increased during the last fifteen years. Bolivia reports the lowest values in this respect. With respect to air pollution, another indicator contributing to Factor 6, Peru, Bolivia, Suriname and Chile report the highest concentrations of fine particulate matter (Indicator 9), and Uruguay, the lowest.

In summary, the above findings reflect clear differences among these twelve South American countries in terms of their environmental sustainability performance, in some cases due to legal initiatives and practices (see Appendix A). In this regard, Chile can be considered a positive benchmark, having enacted new laws on climate change, having created a new, powerful public agency, SBAP, to protect biodiversity (finally established in June 2023, after 13 years' preparation), and having established the National System of Protected Areas, with severe sanctions for non-compliance.

Although predominantly descriptive, this analysis of environmental sustainability performance in twelve South American countries makes a real contribution to our understanding by revealing how and why some countries differ in this respect, and by highlighting the changes needed to enhance performance. In any geographic region with commonalities such as those we describe, it is important to identify and characterize top-performing countries in order to create benchmarks on which others may judge their results.

Among the countries considered, Chile has most improved its environmental sustainability practices, for example by creating a significant marine protected area, thus obtaining competitive and comparative advantages for the development of sustainable aquaculture. Moreover, Chile is a signatory to international agreements against climate change and is making great efforts to achieve carbon neutrality.

The present research also identifies possible advances in theoretical concepts based on the environmental sustainability indicators analyzed, providing valuable empirical information. This is especially important as very few previous studies have adopted such a comparative-international perspective towards the South American region.

Our journey towards sustainability is a process based on a new environmental paradigm, which must guide us towards the changes needed in how resources are managed, in the economic criteria applied, in prevailing values and in the ecological and social practices developed. To be successful in this endeavor, we must alleviate the current deterioration of the global environment and adopt policies in line with the real possibilities of the natural world.

NOTES

Note 1. A Euclidean distance represents the space between two points, measured as a line segment.

Note 2. These treaties and agreements include the Basel Convention, the Stockholm Convention, the Rotterdam Convention, the Minamata Convention, the Vienna Ozone Convention, the Convention on Biological Diversity, the Sustainable Development Goals and the Convention on International Trade in Endangered Species (CITES).

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DECLARATION OF CONFLICTS OF INTEREST

Authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

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Appendix A. South America: Environmental Sustainability Framework Laws

Country	Legislation	Year	Name	Objective
Argentina	Law 27592 or Yolanda	2020	Comprehensive Environmental Training Law for civil servants.	Guarantee comprehensive environmental training, with a sustainable development perspective and with special emphasis on climate change, for public servants.
	Law 27621	2021	Citizenship training.	It proposes the incorporation of environmental contents in the school curriculum and establishes, among other issues, the right to education on this issue as a national public policy.
	Law 25675	2002	General Environmental Law.	Establishes the minimum requirements for the achievement of a sustainable and adequate management of the environment, the preservation and protection of biological diversity and the implementation of sustainable development in Argentina.
Bolivia	Law 1171	2019	Law on the Rational Use and Management of Fires.	Define the guidelines for the policy of integrated fire management in the national territory, establish the regime of administrative sanctions for unauthorized burning and determine an exceptional period of regularization in the payment of debts and fines for unauthorized burning.
	Law 71	2010	Mother Earth Rights Law.	Recognize the rights of Mother Earth, as well as the obligations and duties of the Plurinational State and society to guarantee respect for these rights.
	Law 1333	1992	Environmental Law.	The purpose of this law is the protection and conservation of the environment and natural resources, regulating the actions of man in relation to nature and promoting sustainable development in order to improve the quality of life of the population.
Brazil	Decree 11075	2022	Law decree to regulate the carbon credits market in the country.	Establishes the procedures for the preparation of Sectoral Climate Change Mitigation Plans and establishes the National System for the Reduction of Greenhouse Gas Emissions - Sinare.
	Law 13123	2015	Biodiversity Access Law.	Regulates access to components of the genetic heritage, the protection of and access to related traditional knowledge and the fair and equitable sharing of benefits arising from the conservation and sustainable use of biodiversity.
	Law 9605	1998	Environmental Crimes Act.	It regulates as active subjects of crime any natural person who carries out conducts qualified as crimes under this law, including administrators and legal persons and officials not only by direct action but also by omission.
	Law 6938	1981	National Environmental Law.	The preservation, improvement and recovery of the environmental quality favorable to life, with the objective of guaranteeing, in the country, the conditions for socioeconomic development, the interests of national security and the protection of the dignity of human life.

Continuation Appendix A

Country	Legislation	Year	Name	Objective
Chile	Law 21562 (bill approved by the House July 18, 2023)	2023	Amends Law 19300 on general bases of the environment.	Establish restrictions on the evaluation of projects in areas declared latent or saturated.
	Law 21455	2021	Chile's climate change framework.	Establishes Chile's roadmap towards carbon neutrality by 2050. To face the challenges posed by climate change, moving towards a development low in greenhouse gas emissions and other climate forcing factors, until reaching and maintaining greenhouse gas emissions neutrality by 2050.
	Resolution 79	2021	Regulation on the constitution and operation of the governance implemented within the framework of the water development and sustainability policy for the Valparaíso region.	To execute the Water Policy, the implementation of a "Governance" is considered as a goal to be achieved within the "Governance and Water Management" pillar, a necessary instance that allows for the follow-up and monitoring of the different actions resulting from it.
	Law (SBAP bill passed by the House on July 18, 2023)	2023	Biodiversity and Protected Areas Service Project (SBAP).	Confront the serious crisis of biodiversity loss and climate change that is affecting Chile and the entire world through the creation of a public, autonomous, decentralized service, with robust financing, 100% dedicated to the protection of Chile's natural heritage.
Colombia	Law 11	2021	Crimes against natural resources and the environment.	To replace Title XI, Articles 328 to 339 of Book II, Special Part of Crimes in General of Law 599 of 2000.
	Law 1977	2019	Drinking water and basic sanitation.	Whereby Law 1176 of 2007 is partially amended with respect to the Drinking Water and Basic Sanitation sector".
	Law 1964	2019	Promoting the use of electric vehicles.	Generate schemes to promote the use of electric and zero-emission vehicles, in order to contribute to sustainable mobility and the reduction of polluting emissions and greenhouse gases.
	Law 99	1993	General Environmental Law of Colombia.	Ensure that the occupation models of the Land Management Plans incorporate environmental sustainability and territorial resilience criteria.
Ecuador	Executive Order 59	2021	Establishing the Ministry of the Environment, Water and Ecological Transition.	Declares sustainable development a national priority and mandates the development of incentives for the protection of nature and ecosystems.
	Organic Environmental Code (COA)	2018	Conservation of natural areas and wildlife to climate change, and marine-coastal protection.	Responsibly regulate and manage projects or proposals for anthropic activities so that they do not threaten natural ecosystems.
	Law 37	1999	Environmental Management Law	Establishes the principles and guidelines of environmental policy; determines the obligations, responsibilities, levels of participation of the public and private sectors in environmental management and establishes the permissible limits, controls and sanctions in this area.
Guyana	Parliamentary Resolution No. 45 - National Development Plan about Low Carbon Development Strategy	2022	The new Low Carbon Development Strategy 2030	It will create a new-low-carbon economy in Guyana by establishing incentives which value the world's ecosystem services, and promoting these as an essential component of a new model of global development with sustainability at its core.
	Natural Resource Fund Act 2021 (Act No. 19 of 2021).	2021	Environmental, climate change and sustainable development rights.	Establishes the Natural Resource Fund to manage the natural resources of Guyana for the present and future benefit of the people and the sustainable development of the country.
	NPAP (National Biodiversity Strategy and Action Plan)	2015	National Biodiversity Strategy and Action Plan (2012-2020).	To promote and achieve the conservation of Guyana's biodiversity, to use its components in a sustainable way, and to encourage the fair and equitable sharing of benefits arising out of the use of Guyana's biodiversity".
	Act 11	1996. It was amended in 2005	Environmental Protection Act.	It provides for the management, conservation, protection and improvement of the environment, the prevention or control of pollution, the assessment of the impact of economic development on the environment, the sustainable use of natural resources and other related matters in Guyana.

Continuation Appendix A

Country	Legislation	Year	Name	Objective
Paraguay	Decree 3581	2020	Create the SDG Paraguay 2030 Commission.	To create a new inter-institutional commission called "Comisión ODS Paraguay 2030", for the fulfillment of the international commitments adopted by Paraguay within the framework of the 2030 Agenda for Sustainable Development.
	Law 1561	2000	Law that creates the National Environmental System, the National Environmental Council and the Environmental Secretariat.	To create and regulate the functioning of the bodies responsible for the elaboration, standardization, coordination, execution and supervision of national environmental policy and management in Paraguay. At the same time, it develops issues of participation in plans and policies, and in environmental education.
	Law 716	1995	Law penalizes crimes against the environment.	o protect the environment and the quality of human life against those who order, execute or, by virtue of their powers, allow or authorize activities that threaten the balance of the ecosystem, the sustainability of natural resources and the quality of human life.
Peru	Law 31313	2021	Sustainable Urban Development Law.	Guide the development of cities and population centers to be sustainable, accessible, inclusive, competitive, fair, diverse and just
	Law 28611	1999	General Environmental Law.	General framework for the development and approval of environmental regulations, within the principles of sustainable development.
	Law 26821	1997	Organic Law for the sustainable use of natural resources.	Promote and regulate the sustainable use of natural resources, both renewable and non-renewable, establishing an adequate framework for the promotion of investment, seeking a dynamic balance between economic growth, the conservation of natural resources and the environment, and the integral development of the human person.
Suriname	National Biodiversity Action Plan	2013	National Biodiversity Action Plan.	It defines the main actions to promote greater knowledge and appreciation of our common goods and the ecosystem services they provide.
	National Biodiversity Action Strategy	2007	National Biodiversity Action Strategy.	Formulate policies, initiatives, regulations and procedures that, in a coordinated manner, promote greater knowledge of environmental goods and services and the conservation and protection of biodiversity.
	Nature Conservation Law and Hunting Law	1954 (1992); 1954	Nature Conservation Law and Hunting Law.	Regulates the establishment and management of nature reserves and other protected areas. Hunting law stipulates which species of wild animals may be hunted and during what period. There are four categories of wild animals, namely protected animals, game species, caged species and predominantly harmful species.
Uruguay	Draft Law	2023	Bill to penalize environmental crimes (approved by the Environmental Commission of the Senate).	Criminalize water, air and soil contamination by waste, hazardous substances or wastes, among others.
	Decree 362/022	2022	Modification of decree No. 135/021 Air quality.	Establishing air quality objectives to reduce risks to human health and ecosystems and setting maximum emission limits for both stationary and mobile sources.
	Law 17283	2000	Environmental Protection Act.	To regulate the aforementioned constitutional provision, establishing fundamental rights and duties in environmental matters and providing only for administrative sanctions for infringement of environmental protection norms.
Venezuela	Environmental Criminal Law (Official Gazette 39913)	2012	Venezuelan Environmental Criminal Law.	To classify as crimes those acts that violate the provisions related to the conservation, defense and improvement of the environment, and to establish the corresponding penal sanctions.
	Law 5833	2006	Organic Law of the Environment.	To establish the provisions and guiding principles for environmental management within the framework of sustainable development.
	Law on Hazardous Substances, Materials and Wastes (Official Gazette 5554)	2001	Hazardous Substances, Materials and Waste Law.	To regulate the generation, use, collection, storage, transportation, treatment and final disposal of hazardous substances, materials and wastes, as well as any other operation involving them in order to protect health and the environment.

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