

Sustainability in Mexico: A Socioecological Systems Modeling Approach Using Indicators

Heli Najar (*Facultad de Ciencias, Universidad Nacional Autónoma de México, México*)¹

Edgar J. González (*Facultad de Ciencias, Universidad Nacional Autónoma de México, México*)²
Corresponding author

Abstract:

National sustainability assessments are key to addressing environmental and social issues through evidence-based policies. Given their complexity, a socio-environmental systems (SES) framework is necessary, viewing sustainability as emerging from interconnected components: Economy, Institutions, Society, Anthropogenic Assets, Human Drivers, Ecosystem Services and Nature. We assessed Mexico's state-level sustainability from 2000–2019 using 28 indicators. Missing data were imputed, and principal component analysis reduced dimensionality within SES components. These components formed a Bayesian network to model interrelationships, revealing trade-offs between economic growth and institutional capacity, and strong links between human drivers and environmental impacts. Geospatial analysis showed wide state-level variation, underscoring the need for localized policies. This approach provides a useful model for national sustainability assessments.

Keywords: sustainability assessment; socioenvironmental system; Bayesian networks; Mexican states; indicators

Sustentabilidad en México: un Enfoque de Modelación a través de Indicadores

Resumen:

Las evaluaciones nacionales de sostenibilidad son clave para abordar problemas ambientales y sociales mediante políticas basadas en evidencia. Dada su complejidad, se requiere un marco de sistemas socioambientales (SES) que concibe la sostenibilidad como el resultado de componentes interconectados: Economía, Instituciones, Sociedad, Activos Antropogénicos, Conductores Humanos, Servicios Ecosistémicos y Naturaleza. Evaluamos la sostenibilidad a nivel estatal en México entre 2000 y 2019 utilizando 28 indicadores. Los datos faltantes fueron imputados, y se aplicó análisis de componentes principales para reducir la dimensionalidad dentro de los componentes. Con estos componentes se formó una red bayesiana para modelar las interrelaciones, revelando compensaciones entre el crecimiento económico y la capacidad institucional, así como fuertes vínculos entre los conductores humanos y los impactos ambientales. Un análisis geoespacial mostró una amplia variación entre estados, lo que resalta la necesidad de políticas localizadas. Este enfoque ofrece un modelo útil para las evaluaciones nacionales de sostenibilidad.

¹ Departamento de Ecología y Recursos Naturales, Facultad de Ciencias, Universidad Nacional Autónoma de México, Ciudad Universitaria, Av. Universidad 3000, Circuito Exterior s/n Delegación Coyoacán, C.P. 04510, Mexico City, Mexico, helinajar@ciencias.unam.mx, <https://orcid.org/0009-0000-5171-2436>

² Departamento de Ecología y Recursos Naturales, Facultad de Ciencias, Universidad Nacional Autónoma de México, Ciudad Universitaria, Av. Universidad 3000, Circuito Exterior s/n Delegación Coyoacán, C.P. 04510, Mexico City, Mexico edgarjgonzalez@ciencias.unam.mx, <https://orcid.org/0000-0001-9113-1070>

Palabras clave: evaluación de la sostenibilidad; sistema socioambiental; redes bayesianas; estados mexicanos; indicadores

1. Introduction

Human activities and their impact on ecosystems have made it necessary to adopt sustainability as a key objective to address pressing global challenges such as climate change, pollution, biodiversity loss, land-use change, and poverty (Clark, 2012; Chinedu et al., 2021; Fonseca et al., 2022; Shivanna, 2022; Damor, 2024). In this context, assessing sustainability is essential to determine whether current strategies and actions are effectively contributing to long-term environmental and social well-being.

A practical and conceptually sound way to approach sustainability assessment is to view sustainability as an emergent property of socio-environmental systems. These systems are complex by nature, involving continuous flows of energy and matter, and shaped by dynamic interactions and feedbacks between their components. Specifically, socio-environmental systems are defined by the interplay between society and the environment, where each influences and responds to the other over time. Framing sustainability in this way enables a more integrated understanding of how human and ecological processes co-evolve, and how this co-evolution affects the resilience and functionality of the system as a whole.

In Mexico, the development and use of sustainability indicators have been actively promoted by both national and international institutions. Several systems of indicators have been established, including those aligned with the Sustainable Development Goals (SDGs) (UN, 2015), the National System of Environmental and Natural Resource Information (SNIARN; SEMARNAT, 2024), the National Institute of Statistics and Geography (INEGI) Indicator Bank, and the Climate Change Special Indicators (SEMARNAT, 2021), among others. Since 2015, the SDGs have guided Mexico's integration into the 2030 Agenda, providing a framework for evaluating progress toward sustainability. Most indicators are available at the national level, although disaggregated data also exist at state and municipal scales. These indicator systems address a range of thematic axes, including social, environmental, and economic dimensions. For instance, SNIARN has published primarily environmental indicators since 2000, with a focus on the management and conservation of Mexico's natural resources, and offers data at national, state, and local levels. INEGI, on the other hand, has compiled social and demographic indicators since the 1940s, available at national and state scales.

Assessing the sustainability of a socio-ecological system requires not only a robust set of indicators but also a conceptual framework that articulates how these indicators relate and interact—ultimately reflecting the system's internal feedbacks. Various conceptual models have been developed to structure this type of analysis, including: PSR (Pressure–State–Response) (OECD, 1993), DPSEEA (Driving force–Pressure–State–Exposure–Effect–Action) (Briggs, 1999), DSR (Driving force–State–Response) (OECD, 1999), DPSIR (Driving force–Pressure–State–Impact–Response) (Vázquez-Valencia, 2018), ESALC (Environmental Sustainability for Latin America and the Caribbean) (Gallopín et al., 2006), The Capital Approach (Atkinson, 2008), The SES Framework (Ostrom, 2009), and the IPBES Conceptual Framework (Binder et al., 2013; Díaz et al., 2015).

First-generation models such as PSR and DPSIR offered useful starting points for understanding human-environment interactions. However, they are now considered limited, as they focus primarily on environmental dimensions and can be ambiguous—making it difficult to consistently classify indicators or represent complex interdependencies. For example, a single variable may function simultaneously as a pressure and a state, and multiple pressures may lead to overlapping states.

In contrast, the IPBES conceptual framework presents a more integrative and interdisciplinary approach. It explicitly links biodiversity conservation and ecosystem services to human well-being and sustainable development. By incorporating ecological, social, and economic dimensions, and allowing for application across different spatial and temporal scales, the IPBES model provides a flexible and comprehensive foundation for scenario development and sustainability assessment.

Given that the sustainability assessment of a socio-ecological system can inform and support decision-making processes (Chai et al., 2020; Zhang et al., 2022; Polido, 2023), this study aims to

evaluate the sustainability status of Mexico at the state level, using a socio-ecological systems perspective. We integrate information from multiple sustainability indicators, spanning the period from 2000 to 2019, and apply a Bayesian modeling approach to estimate the degree of sustainability achieved by each Mexican state. This model enables us to explore how various components of the socio-ecological system interact and contribute to different sustainability outcomes.

2. Methods

2.1 Conceptual model

Following a review of conceptual frameworks on socioecological systems (Smeets & Weterings, 1999; Folke et al., 2004; Östrom, 2009; Diaz et al., 2015; Turner et al., 2016; IPBES, 2019; Clark & Harley, 2020), we created a conceptual model of a socioecological system and its functioning. The components proposed for such system model were: 1) *Economy*, includes economic activities, as well as important data on the country's economic status; 2) *Institutional*, which includes aspects of governance related to the public administration and the policies that impact on the Society; 3) *Society*, includes aspects of people's daily lives that describe their status in the categories of health, education, food, quality of life, etc.; 4) *Anthropogenic Assets*, includes activities such as infrastructure, health facilities, knowledge, technology, and financial assets (Diaz et al., 2015); 5) *Human Drivers*, includes human actions that have an impact on the environment; 6) *Ecosystem Services*, includes benefits from the ecosystem to the society, which can improve people's health and economy, provide services and leisure, etc; 7) *Nature*, includes qualities of the ecosystems. These components were interconnected to represent their interactions (Fig. 1).

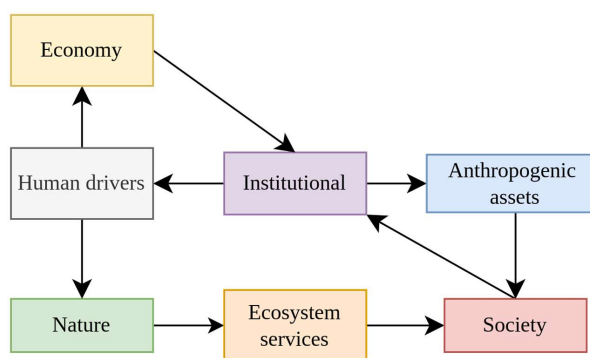


Figure 1. Conceptual model of the dynamics of a general socioecological system

The relationships proposed in the model (Fig. 1) are as follows: Society is related to Anthropogenic Assets, Economy, and Ecosystem Services (Chiabai et al., 2018; Leviston et al., 2018; Sambo et al., 2024) because society relies on built infrastructure and human-created systems (Anthropogenic Assets) to meet its needs, drives economic activity, and benefits directly from the goods and services provided by natural ecosystems. Institutional is related to Society because policies, governance, and social norms shape societal behaviors and decision-making, creating feedback loops that impact both economic and environmental outcomes (Sarkki et al., 2017). Anthropogenic Assets are related to Institutional since regulatory frameworks, investments, and institutional planning dictate the development, maintenance, and sustainability of human-made infrastructure (Chai et al., 2020). Economy is related to Institutional because government interventions, financial policies, and public regulations influence economic growth, distribution of resources, and market dynamics. Human Drivers are connected to Institutional because human actions—such as land-use changes, resource consumption, and pollution—are often regulated or influenced by institutions that aim to balance development and environmental sustainability. Ecosystem Services are related to Nature because they arise from the

healthy functioning of ecosystems, such as clean air, water purification, and biodiversity support (Hanes et al., 2018; Yuan & Lo, 2020). Nature is linked to Human Drivers because human activities can significantly alter ecosystems, either degrading or enhancing the natural processes that sustain life on Earth. This web of interconnected relationships highlights the complex and dynamic interactions necessary for sustainability and resilience in socio-ecological systems.

After a literature search associated with sustainability, international and national sustainability indicators for Mexico we found 36 articles in Google Scholar with the keywords: indicators, sustainability, Mexico; this search was performed during April-March of 2019. These articles served as a guide to find sustainability indicator systems and databases applicable to Mexico. The selection of indicators for each component of the model was made considering their relevance, quality, frequency and availability (Schuschny, 2009). Initially 193 indicators were considered, but the number was reduced to 28 because no information was available for the time scale (2000-2019) and spatial scale (federal state level) used. Due to the lack of data for years prior to 2000, we used the years with the most data available, which correspond to the years 2000 to 2019. The 28 selected indicators displayed different degrees of missing values, and an imputation procedure was followed to fill in these data gaps. Each indicator was imputed according to the range of values it displays: percentage, non-negative or positive (Brooks et al., 2017). Once imputed, the variables were standardized, i.e., we subtracted from the variable values their mean and divided them by their standard deviation.

2.2 Principal Component Analysis

To reduce the dimensionality of each component of the conceptual model, a principal component analysis (PCA) was conducted on the indicators associated with five of the seven model components (Fig. 1); those that had more than two indicators; two dimensions were selected from each PCA. The assignment of each indicator to a dimension was based on its PCA score. Subsequently, these dimensions were used instead of the individual indicators for each component, except for the Nature and Anthropogenic Assets components. With these reduced indicators, we constructed a Bayesian network. Performing a PCA was useful for: 1) using it in the construction of the Bayesian network, and 2) understanding which indicators are more closely related to each other and grouping them.

2.3 Bayesian network

In recent years, the use of Bayesian networks (BN) has increased as a tool to analyze and apply a conceptual model in a complex system. A BN is a graphical probabilistic model that represents a set of variables, in this case, indicators, and the dependency relationships between them through a directed acyclic graph (DAG) (Nagarajan et al., 2013). We decided to construct a Bayesian network because it is useful in capturing complex relationships, as in this case where we have a large number of interconnected indicators. It also allows us to address the uncertainty arising from the data or the model. Another important point is the exploration of causal relationships, as it helps to understand how one indicator can affect another. Finally, another reason for developing a Bayesian network was grouping and simplification, as with a considerable number of indicators, addressing the system's complexity can be challenging. Other applications that we did not explore in this work but are part of the applications of Bayesian networks include simulation and prediction, as well as informed decision-making.

We constructed the Bayesian network using the reduced indicators as input and the conceptual model as its structure. The result of the Bayesian network was a model that displays the strength of relationships between dimensions/components of the proposed model. This is a crucial step because it allows us to observe whether the Bayesian network supports the relationships we proposed, although this may be constrained by the quantity and availability of data used for the PCA and the Bayesian network itself. The network was constructed in R (R Core Team, 2024) using the bnlearn package (Scutari, 2021).

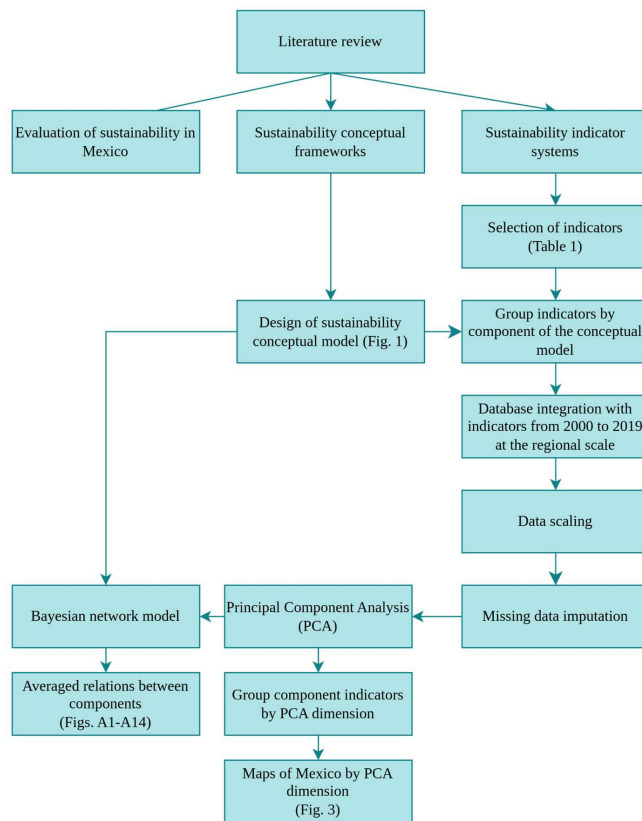


Figure 2. Method flowchart followed in this study.

2.4 Mapping components

Maps of Mexico were generated in R (Valle-Jones, 2022) showing the states with the average score for each component. This information allows us to identify which states have higher or lower values and to relate these results to the existing literature. To make these maps, the following steps were carried out: 1) averaging the value of each indicator for each state, 2) grouping the indicators by component and averaging again for each state, and 3) calculating a general average; that is, a national average for each component. The value of the national average was subtracted from the average value obtained for that state, and the resulting value was used to make the maps for Mexico. It is important to mention that for these averages the positive or negative connotation of the indicators in terms of sustainability was considered.

3. Results

After searching for conceptual frameworks, indicators and indicator systems, the following sources of indicators for Mexico were identified: Statistical Database of the National System for Environmental and Natural Resources Information (BADESNIAR), National System of Environmental Indicators (SNIA), National System of Geographic and Statistical Information (SNIEG) the and Sustainable Development Goals Indicator System (SDGIS). A total of 28 indicators were selected (Table 1),

consisting of four *Economy* indicators, four *Institutional* indicators, ten *Society* indicators, two *Anthropogenic Assets* indicators, four *Human Drivers* indicators, three *Ecosystem Services* indicators, and one indicator for *Nature*. Table 1 contains details on the characteristics of these indicators.

Table 1. Indicators selected to describe the current status of the components of the conceptual model describing the socioecological system associated with Mexico. PCAD, principal component analysis dimension to which each indicator belongs; SS, sustainability sign.

Component	Indicator	Acronym	PCAD	Description	Units	SS
Economy	Self-employed workers	WL	1	Proportion of self-employed and unpaid workers	%	-
	Unemployment	UE	1	Unemployment rate	%	-
	Female employees	FE	2	Proportion of women in the total number of salaried employees in the non-agricultural sector	%	+
	Worker population	WP	2	Ratio of occupation to working-age population	%	+
Ecosystem Services	CONAFOR Area	CA	1	Area benefited by the National Forest Soil Program of CONAFOR	ha	+
	Timber amountable	TA	1	Authorized amount of timber forest	m ³	-
	Reforestation	R	2	Reforested area	ha	+
Society	Diarrheal diseases	DD	1	Mortality rate in children under 5 years of age due to diarrheal diseases	%	-
	Elementary school	ES	1	Terminal efficiency in elementary school	%	+
	High school	HS	1	Terminal efficiency in high school	%	+
	Literacy	L	1	Percentage of the population in a given age group that achieves at least a fixed level of functional competence in a) literacy and b) elementary numeracy	%	+
	Maternal mortality	MM	1	Maternal mortality ratio	%	-
	Respiratory diseases	RD	1	Mortality rate in children under 5 years of age due to acute respiratory diseases	%	-
	AIDS mortality	AIDS	2	AIDS-related mortality rate	%	-

	Complete vaccination	CV	2	Proportion of one-year-old children with a complete basic vaccination schedule	%	+
	Malaria	M	2	Incidence rate associated with malaria	%	-
	Measles vaccination	MV	2	Proportion of one-year-old children vaccinated against measles	%	+
Institutional	CONAFOR Budget	CB	1	Exercised budget of the National Forest Soils Program of CONAFOR	pesos (mxn)	+
	Natural disasters	ND	1	Natural Disaster Fund: Federal expenditure authorized by Branch 23 and the FONDEN Trust by federal entity	millions of pesos (mxn)	+
	Female deputies	FD	2	Composition of local congresses by sex	%	+
	Human Development Index	HDI	2	Human Development Index, UNDP	-	+
Nature	Pest affectation	PA	-	Forest area affected by pests: Total Area/Diagnosis	ha	-
Anthropogenic Assets	Paved road	PR	-	Length of the road network by state: paved/total	km	+
	Total road	TR	-	Length of the road network by state: Total	km	+
Human Drivers	Aquaculture	AQ	1	Aquaculture production by coast and state (tons)	tons	-
	Crop irrigation	CI	1	Total harvested irrigation area	ha	-
	Controlled urban waste	CUW	2	Proportion of estimated disposal of urban solid waste by federal entity Controlled sites among total controlled and uncontrolled sites plus recycling	millions of tons	+
	Rainfed harvest	RH	2	Total harvested rainfed area	ha	+

3.1 Analysis of the relationships between components

The analysis of each component within the conceptual model (Fig. 1) revealed various interdependencies among institutional, economic, social, and environmental factors.

Institutional factors, particularly those related to public budgets such as the CONAFOR Budget and the Natural Disasters Fund, were closely linked to economic and social dynamics. Self-employment and unpaid work showed positive correlations with institutional budgets, whereas higher unemployment, a larger working population, and more salaried women were associated with budget reductions. A second institutional dimension highlighted that increases in self-employment corresponded with decreases in the Human Development Index (HDI) and the proportion of women in parliament. Similarly, higher unemployment rates tended to correlate with lower HDI values. Economic components revealed links between occupational patterns and the working-age population.

Regarding *Anthropogenic assets*, HDI was positively associated with road infrastructure, suggesting that more developed regions had better connectivity. However, there was also a tendency for regions with lower HDI and fewer women representatives to receive more infrastructure investment.

In the *Human drivers* dimension, HDI was negatively associated with aquaculture, while public budgets supported expansion in aquaculture and irrigation activities. Waste management appeared to decline as budgets increased, and lower HDI regions experienced reductions in rainy season harvests and waste control. Pest infestations were linked to decreases in aquaculture, irrigation, and waste management, but to increases in rainy harvests.

Economic trends showed that self-employment contributed to lower urban waste control but higher temporary crop harvesting. Unemployment was linked to reduced aquaculture activity and increased waste generation. Additionally, regions with a larger working population and more salaried women tended to show increased urban waste and decreased reliance on rainfed agriculture.

In terms of *Ecosystem services*, higher pest incidence had a negative effect on reforestation efforts.

Finally, within the *Social* component, self-employment and infrastructure development were associated with increases in diarrheal disease rates and declines in employment and literacy. Unemployment was linked to lower immunization coverage, while self-employment negatively affected vaccination and malaria control efforts. Institutional budgets also showed correlations with adverse health and education outcomes, including increased mortality from certain diseases and reduced access to basic education and preventive healthcare.

3.2 Maps of components

Using the values from the Bayesian network, averages were calculated to show the level of sustainability of each state's components (Figs. 3B-H). The states with the highest average sustainability scores were Nuevo León, Jalisco, Guanajuato, and Guerrero, while the states with the lowest average scores were Yucatán, Campeche, Tabasco and Sinaloa (Fig. 3A).

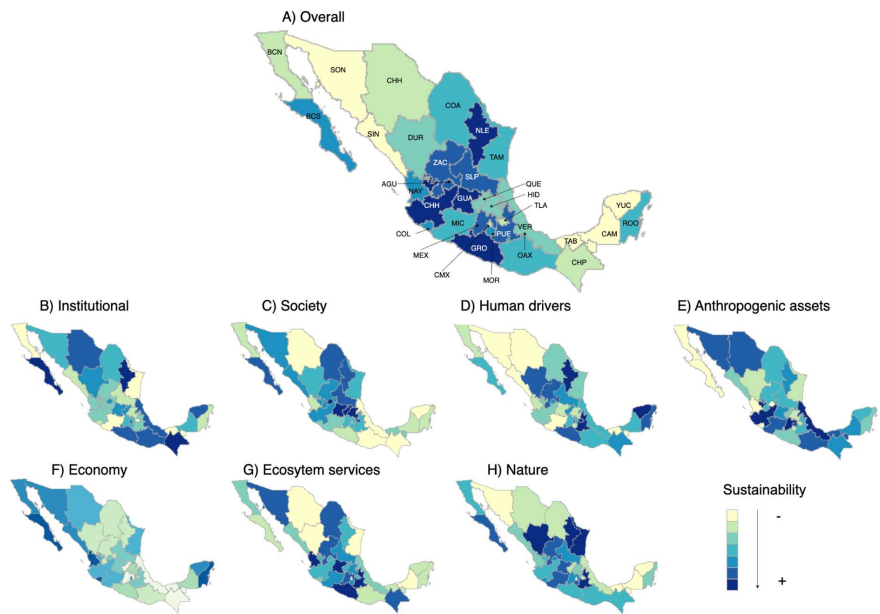


Figure 3. Maps presenting the sustainability status for each Mexican state. A) overall sustainability status; B)–H) component specific sustainability statuses.

For most of the components, the lowest values are found in the south of Mexico. Some states such as Baja California Sur, Nuevo León and Mexico City stand out in most components. The states in central Mexico (such as Guanajuato, Michoacán, and Jalisco) appear to exhibit greater sustainability compared to regions in the north and southeast. The regions with the strongest *institutional* performance are located in central Mexico and parts of the north, while the south and southeast display lighter shades, indicating lower levels of institutional sustainability. *Social* patterns are similar to institutional ones, with the central and northern areas showing higher sustainability. This may suggest that social development and institutional systems are correlated in these regions. *Human Drivers* exhibits a more varied distribution. The central region appears at a moderate level, while certain areas in the south, such as Chiapas and Oaxaca, display a lower development in this category. Areas with higher concentrations of *anthropogenic assets* are located in the north, the center, and some coastal zones, such as Baja California and Yucatán. Northern states, such as Baja California and Nuevo León, show stronger economies compared to the southern regions. With respect to *ecosystem services*, there is an interesting distribution, with certain southern states, such as Chiapas and Oaxaca, showing better ecosystem services. *Nature* patterns highlight areas with high biodiversity or conservation efforts, particularly in the south and along some states on the Pacific coast.

A clear geographic pattern emerges in the analysis: the northern and certain central areas of the country score higher in economy and anthropogenic assets, while the southern region excels in ecosystem services and natural resources. Additionally, there is a concentration of high institutional and social component levels in the central states, which may imply a correlation between institutional and social development, and central geographic location. The similarity observed in the spatial patterns of Economy and Anthropogenic Assets in the northern and central regions suggests an interrelationship between these components, potentially due to a stronger economy enabling greater investment in infrastructure.

3.3 Value of the relationships established by the model

After reviewing the relationships between the components and their dimensions, we calculated average size effect values to quantify these relationships (Fig. 2). The Economic → Institutional relationship was the strongest, with a negative size effect of -0.30. This was followed by a negative Anthropogenic Assets → Society relationship, and a negative Nature → Ecosystem Services relationship. The weakest relationships were Human Drivers → Nature, Society → Institutional, and Ecosystem Services → Society, with the first two being negative and the last one being positive.

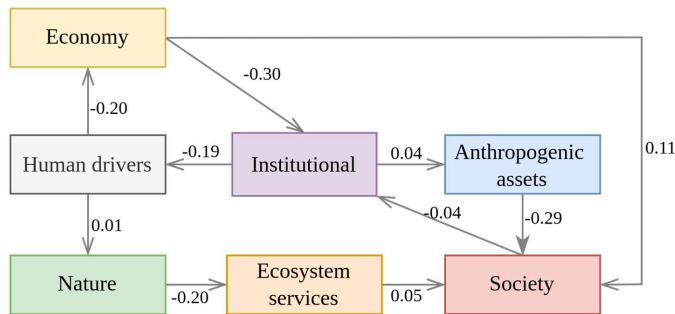


Figure 4. Conceptual model with the estimated average effects between components obtained through a Bayesian network model.

4. Discussion

The results presented highlight the complex interrelationship among institutional, economic, social, anthropogenic assets, human drivers, ecosystem services, and nature itself, as well as the marked regional variations in sustainability across different areas of Mexico. These correlations, both positive and negative, underscore the need for comprehensive approaches that recognize the interdependence between social and environmental actors. In the following discussion section, the significance of these findings will be explored in greater depth, contrasted with previous studies, and potential implications will be evaluated to guide policies and sustainable management strategies that address the complexity of socio-ecological systems in the country.

4.1 Relations with the Institutional component

The Institutional component reflects the connection between economic dynamics and institutional funding mechanisms, such as the CONAFOR budget and the Natural Disasters Fund (Table 1). Evidence suggests a link between the proportion of self-employed workers, who predominantly work in sectors like agriculture, trade, tourism, and construction (Hurst et al., 2007), and government support programs. The fluctuating budget of CONAFOR in recent years (De la Rosa, 2021) and associated workforce reductions exemplify how institutional funding responds to economic pressures and workforce dynamics, underscoring the interdependence of institutional and economic components.

Another key observation within this component is the interaction between labor demographics, such as the working-age population and salaried women, and the CONAFOR budget. A larger working-age population correlates with reduced budget allocations, reflecting how budget priorities may shift in states with more formalized labor markets. This dynamic can be seen in states with substantial CONAFOR and Natural Disasters funding but low employment rates for women, suggesting potential biases in budget allocation influenced by local workforce characteristics like Guerrero and Chiapas. Additionally, the low female labor force participation rate in Mexico (Inchauste Comboni et al., 2021), despite recent increases (Castillo, 2023), reflects how socio-economic shifts impact employment and

subsequently, institutional funding.

The second dimension of the Institutional component centers on the Human Development Index (HDI) and gender representation in local congresses. Research suggests that self-employed and unpaid workers, often earning lower wages, have a lower HDI than salaried employees (UNDP, 2015). This correlation emphasizes how income stability directly affects human development, as defined by expanding human capabilities (López & Vélez, 2003). Additionally, the relationship between gender representation and economic stability is notable; as female representation in local congresses increases, employment metrics among self-employed and salaried women improve, highlighting the socio-economic impact of gender equity in governance (INMUJERES, 2022). Gender representation in parliament not only supports broader human development but also reflects Mexico's efforts toward political gender parity (Inchauste Comboni et al., 2021).

The institutional component reflects the complex relationship between budget allocations and socio-cultural factors across Mexican states. Three of the indicators focus on budgetary aspects, which may introduce bias, as budget distribution varies significantly between states (CONAFOR Budget, Natural Disasters Fund). Furthermore, the gender equity indicator (composition of local congresses by sex) responds to socio-cultural dynamics that the model does not account for. To more accurately represent institutional strength, additional measures that consider socio-cultural influences and equitable budget allocations would be beneficial.

4.2 Relations with the Anthropogenic Assets component

Anthropogenic assets, such as road infrastructure, demonstrate a crucial relationship with the institutional and society components, as infrastructure facilitates social development through improved quality of life and economic opportunities (IPBES, 2019; Zepeda-Ortega, 2019). The literature emphasizes that road infrastructure positively impacts property value, vehicle ownership, and home improvements (Gonzalez-Navarro & Quintana-Domeque, 2016), aligning with findings that infrastructure investments enhance societal well-being. Moreover, the interaction between road infrastructure and the HDI suggests that regions with extensive infrastructure enjoy a higher standard of living, demonstrating the fundamental role infrastructure plays in development (Perez, 2008).

The relationship between infrastructure and institutional funding, although weak, further suggests that as road networks expand, so do budgets for environmental and disaster management, emphasizing the role of infrastructure in development planning. This component highlights how infrastructure investments serve as a catalyst for socio-economic progress, influencing education, healthcare, and transport, thus supporting a holistic approach to development.

According to the National Highway Network, in 2022 the states with the longest highways were: Chihuahua, Sonora, Veracruz, Jalisco, Chiapas, Oaxaca, Durango, Michoacán, Tamaulipas and Guerrero (IMT, 2022). Some of them match the data available until 2019. These states are characterized by being states that export products to the rest of the country, or outside of it; this is related to the fact that the sector most benefited by investment is the industrial sector in those same areas. But it is important to acknowledge that roads also respond to questions of population density and the geography of the territory, so in some places, although there are roads, they are not completely paved, or in other areas geography makes the task of road construction almost impossible. As we can see, the construction of new roads and roads responds mainly to economic demands such as export and import, as well as the extension of urban territory, but through institutional decisions, as most road building is performed by the Mexican government.

Recalling that this component not only includes infrastructure, but also advances in science and technology, the catalogue of indicators could be expanded with information related to these areas.

4.3 Relations with the Human Drivers component

The Human Drivers component, encompassing primary activities (agriculture, aquaculture) and urban waste management, underscores the impact of rural economies on natural resources (FAO, 2012). Rural areas, where poverty rates are higher, often show a stronger reliance on irrigation-based agriculture, aligning with socio-economic vulnerabilities linked to agricultural employment (IBRD, 2021). The

component also highlights the critical role of urban waste management, with urban centers being major consumers of resources and contributors to greenhouse gas emissions (McPhearson, 2016). Effective waste management in cities not only enhances environmental quality but also mitigates climate change impacts, underscoring urban areas as pivotal sites for sustainable practices.

This component further suggests a socio-economic divide in waste management infrastructure, with wealthier urban areas displaying higher levels of controlled waste disposal than rural regions. This aligns with the observation that states receiving CONAFOR funding often correlate with higher rural populations engaged in primary activities, highlighting disparities in resource distribution and infrastructure access.

The Human Drivers component currently includes indicators like aquaculture, urban waste, and agricultural production. States leading in agriculture, such as Puebla, and those in aquaculture, like Yucatán (Soto-Mora, 2003; SEMARNAT & CONAGUA, 2019; CEDRSSA, 2020), show notable contributions. Yet, the set of indicators in this component is limited, which may explain the low relation with the Nature component; incorporating additional indicators—such as tourism, security, and violence—would allow for a more holistic view of human activities impacting the environment.

4.4 Relations with the Nature component

The Nature component focuses on the significant impact of pests on agricultural productivity, highlighting how pest control is deeply intertwined with both environmental and socio-economic factors (FAO, 2019). According to CONAFOR, the most affected areas are those plagued by parasitic plants, insects, and defoliators (CMICEF, 2021). However, pest management is not solely a technical or ecological issue—social challenges such as land tenure disputes and insecurity further complicate efforts to control outbreaks (CMICEF, 2021). Adaptive strategies, such as crop insurance for high-risk crops like maize and sorghum, attempt to mitigate economic losses (SADER, 2016, 2022). Still, the interplay between pest dynamics and socio-political barriers remains underexplored and demands greater attention in both policy and practice.

In its present form, the Nature component, focusing on pest impact, lacks representation of other critical ecological factors that affect environmental sustainability. Integrating additional indicators, such as rainfall, biodiversity, and soil quality, would better reflect the diverse environmental conditions across states and provide a more complete picture of ecological health.

4.5 Relations with the Economy component

The Economy component shows a relationship between self-employment and urban waste, where self-employed workers often face economic insecurity due to lower income and limited access to health services (Areous, 2011). This is particularly evident in informal employment sectors lacking infrastructure and social safety nets, which highlights the precarious nature of self-employment in regions with limited institutional support. Furthermore, urban waste levels correlate with population density, with more populated and economically active states generating higher levels of waste.

The employment-waste relationship within this component reinforces the socio-economic divide, as urban waste management infrastructure is often concentrated in economically prosperous areas. Thus, regions with a higher concentration of salaried women and working population, who contribute to economic activities, show improved waste management practices, reflecting socio-economic influences on environmental practices.

The economic indicators in this research capture socio-economic elements rather than providing a complete picture of state-level economic performance. While certain states contribute significantly to GDP, especially in primary, secondary, and tertiary activities (INEGI, 2020), the limitations of spatial and temporal indicators restrict a full economic assessment. A more nuanced approach with additional economic indicators would better align this component with actual economic performance across Mexican states.

4.6 Relations with the Ecosystem Services component

The Ecosystem Services component emphasizes the importance of forestry in providing essential goods and services, including timber and reforestation, which are directly impacted by environmental threats like pests and deforestation (FAO, 2018). Forests, particularly in states with high pest incidences, face sustainability challenges due to climate change, overexploitation, and natural resource mismanagement (Vega, 2022). The decline in the CONAFOR budget amid rising pest threats emphasizes the need for robust institutional support to preserve forest ecosystems, as their degradation impacts both biodiversity and the economy.

This component is currently focused on forestry-related activities, highlighting states with significant tropical and temperate forests. However, this focus omits other important ecosystem services and types of ecosystems. Adding indicators for a broader range of ecosystems would provide a more comprehensive understanding of ecosystem services, reflecting the biodiversity and ecosystem variety found across Mexico's diverse landscapes.

4.7 Relations with the Society component

The Society component reflects the intersections between socio-economic factors and public health. Our indicators of literacy, education, and disease prevalence reveal the effects of economic stability on quality of life.

Health outcomes are strongly linked to socio-economic conditions, particularly in poverty-stricken regions. For example, diarrheal diseases are prevalent in areas with limited economic activity, where maternal education, malnutrition, and poverty contribute to higher disease incidence (Rivera et al., 2004; Olaiz-Fernández et al., 2020). Respiratory and maternal health issues are also more common in poorer regions due to environmental risks, limited healthcare access, and economic disadvantages (OMS, 2018; UNFPA, 2018a, 2018b). Similarly, HIV-AIDS mortality rates tend to be higher in areas with fewer economic resources, emphasizing the role of timely diagnosis and healthcare access in disease management (ONU, 2011; UNAIDS, 2011). Chronic illnesses such as heart disease, diabetes, and respiratory infections further highlight Mexico's public health challenges (Ferreira-Guerrero et al, 2013; INEGI, 2022).

Educational attainment reflects economic disparities, with states in southern Mexico experiencing lower literacy and school attendance rates due to structural inequalities. In regions like Chiapas and Oaxaca, high educational backlog limits opportunities for social and economic progress (INEGI, 2020; CONEVAL, 2022a, 2022b). Education plays a crucial role in poverty reduction (Tapia, 2016), yet limited access and underfunding in healthcare (Medina, 2020) hinder development efforts.

Expanding the Society component to include additional indicators focused on childhood welfare would provide a more nuanced view of social challenges, particularly those affecting vulnerable populations (Lustig, 2007; Rojas, 2017). Addressing disparities in health and education is essential for improving overall societal well-being and aligning with global sustainability goals.

4.8 General sustainability patterns

States with the highest sustainability scores are Nuevo León, Jalisco, Guanajuato, and Oaxaca, while Sinaloa, Sonora, Campeche, Yucatán, and Tabasco scored the lowest. Sustainability reports in Mexico often focus on cities (Aguilar, 2008), and thus it is not easy to compare our results with existing studies. This focus is driven primarily by the concentration of data, resources, and population in urban areas. Research initiatives and public policies tend to prioritize urban planning and their environmental challenges, such as pollution, mobility, and urban sprawl, while rural areas, which face equally significant issues (land use, food security, and biodiversity conservation), receive less academic and media attention. This imbalance limits a comprehensive understanding of sustainability challenges at the national level.

Interestingly, different factors influence a state's sustainability score. For example, Mexico City, despite its high HDI, scores low in Nature, Ecosystem Services, and Society due to its high urbanization and limited space for nature. Conversely, Guerrero performs unexpectedly well in several components like Ecosystem Services and Human Drivers, boosting its sustainability score. Overall, most Mexican states fall in the middle range of the sustainability score, contrasting with Mexico's

70.4/100 compliance score for the UN's sustainable development goals (CINU, 2021). Achieving true sustainability will require improvements in practices and goal-setting, alongside better evaluation methods.

4.9 Study limitations

Representing reality through models is complex, particularly when identifying key components and relationships. This research proposes a conceptual model of sustainability based on a socioecological vision, including seven components: Nature, Economy, Ecosystem Services, Human Drivers, Society, Anthropogenic Assets, and the Institutional component. Inspired by the IPBES framework, the model aims to simplify complex socioecological systems and facilitate interdisciplinary analysis (Díaz et al., 2015). Once developed, the conceptual model was implemented with data from a variety of sources sought to represent the different model components. However, development and implementation procedures could be improved. For example: 1) the conceptual model was designed from an anthropocentric perspective; there is a risk of being reductionist, focusing on environmental economics rather than holistic socioecological systems; 2) the model lacks certain relationships between components, which emerged during the analysis and could enhance feedback loops; 3) the sustainability model relies on an unequal number of indicators for each component (e.g., Nature only has one indicator, while Society has ten), which may introduce bias; new indicators related to problems like security, biodiversity, and climate could be introduced to provide a more comprehensive view; 4) the indicators used in the model reflect specific institutional interests, and their subjective nature may influence the evaluation of sustainability; 5) the quality and quantity of data were insufficient, and information gaps in the indicator time series, particularly during the COVID pandemic, affected the model; while new indicators like internet access and happiness could enrich the model, historical data is lacking, making their inclusion difficult; many existing sustainability indicator systems (e.g., CSD, SDG, BADEIMA) offer a broader scope that could address gaps in topics like health, education, climate change, and biodiversity; some SDG indicators, though useful, may not fully capture reality (e.g., primary education completion rates overlook education quality), suggesting a need for more interdisciplinary and descriptive indicators to better assess sustainability across multiple dimensions.; and 6) the imputation process we used inserts an element of uncertainty in our results. These considerations could have various degrees of impact on our results and make this exercise difficult to replicate with exactly the same data.

5. Conclusions

Sustainability in the Mexican states is a multifaceted construct shaped by economic strength, institutional efficacy, social development, environmental resources, and ecosystem services, with distinct northern, southern and central patterns. Our modelling approach, which integrates various sustainability indicators within a Bayesian framework, provides a pioneering lens to evaluate sustainability in Mexico, revealing regional strengths and areas needing policy focus. Importantly, the study emphasizes that sustainability is dynamic and context-sensitive; thus, refining this model with additional indicators—such as those related to social equity, human welfare, and environmental resilience—can enhance its applicability, making it an invaluable tool for targeted, data-driven policy making in sustainable development across Mexico.

Acknowledgements

We thank Guillermo Murray-Tortarolo, G. Carlo Delgado, Patricia Ávila-García and Omar Arellano-Aguilar for providing useful comments on a previous version of this manuscript.

References

Aguilar, A. G. (2008). Peri-urbanization, illegal settlements and environmental impact in Mexico City. *Cities*, 25(3), 133–145. <https://doi.org/10.1016/j.cities.2008.02.003>

- Areous, B. G. I. (2011). *Estado, mercado y familia en México: distinguiendo el sentido del bienestar en los trabajadores por cuenta propia* [Master's thesis, FLACSO Ecuador]. Repositorio Digital FLACSO Ecuador. <https://repositorio.flacsoandes.edu.ec/handle/10469/2916>
- Atkinson, G. (2008). Sustainability, the capital approach and the built environment. *Building Research & Information*, 36(3), 241–247. <https://doi.org/10.1080/09613210801900734>
- Bell, S., & Morse, S. (2012). *Sustainability indicators*. Routledge. <https://doi.org/10.4324/9781849772723>
- Binder, C. R., Hinkel, J., Bots, P. W. G., & Pahl-Wostl, C. (2013). Comparison of frameworks for analyzing social-ecological systems. *Ecology and Society*, 18(4), 26 <http://dx.doi.org/10.5751/ES-05551-180426>
- Briggs, D. (1999). *Environmental health indicators: Framework and methodologies*. World Health Organization. https://apps.who.int/iris/bitstream/handle/10665/66016/WHO_SDE_OEH_99.10.pdf
- Brooks, M. E., Kristensen, K., van Benthem, K. J., Magnusson, A., Berg, C. W., Nielsen, A., Skaug, H. J., Maechler, M., & Bolker, B. M. (2017). glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. *The R Journal*, 9(2), 378–400. <https://doi.org/10.32614/RJ-2017-066>
- Castillo, T. B. & Villa, S. A. (2023, March 7). *Fortalecimiento de la participación laboral femenina: Recuperación post pandemia*. Retrieved May 27, 2025, from <https://ciep.mx/fortalecimiento-de-la-participacion-laboral-femenina-recuperacion-post-pandemia/>
- CEDRSSA. Centro de Estudios para el Desarrollo Rural Sustentable y la Soberanía Alimentaria. (2020). *Situación del Sector Agropecuario en México*. Cámara de Diputados. Retrieved July 29, 2021, from http://www.cedrssa.gob.mx/post_situacinin_del_-n-sector_agropecuario-n_en_mn-xico.htm
- Chai, J., Shi, H., Lu, Q., & Hu, Y. (2020). Quantifying and predicting the Water-Energy-Food-Economy-Society-Environment Nexus based on Bayesian networks - A case study of China. *Journal of Cleaner Production*, 256, 120266. <https://doi.org/10.1016/j.jclepro.2020.120266>
- Chiabai, A., Quiroga, S., Martínez-Juarez, P., Higgins, S., & Taylor, T. (2018). The nexus between climate change, ecosystem services and human health: Towards a conceptual framework. *Science of the Total Environment*, 635, 1191–1204. <https://doi.org/10.1016/j.scitotenv.2018.03.323>
- Chinedu, A. C., Amere, L. T., Jeminat, S., Ololade, F., & Dandam, K. N. (2021). Anthropogenically induced ecosystem dysfunction and human health. *African Journal of Environment and Natural Science Research*, 4(3), 48–58. <https://doi.org/10.52589/ajensr-w0lhry0n>
- CINU. Centro de Información de las Naciones Unidas en México. (2021). *México cumple con 70.4 en los ODS*. <https://mexico.un.org/es/155256-m%C3%A9xico-cumple-con-704-en-los-ods>
- Clark, B., & Bellamy Foster, J. (2012). Imperialismo ecológico y la fractura metabólica global. Intercambio desigual y el comercio de guano/nitratos. *Theoria*, (26), 1–25. <https://www.redalyc.org/articulo.oa?id=12426097005>
- Clark, W. C., & Harley, A. G. (2020). Sustainability science: Toward a synthetic framework for sustainable development. *Annual Review of Environment and Resources*, 45, 331–386.
- CMICEF. Centro Mesoamericano para el Intercambio de Conocimientos y Experiencias Forestales. (2021). *Situación de plagas forestales en México: Avances y retos*. CMICEF. Retrieved May 27, 2025, from <https://cmicef.org/situacion-de-plagas-forestales-en-mexico-avances-y-retos/>
- CONEVAL. Consejo Nacional de Evaluación de la Política de Desarrollo Social. (2022a). Panorama del rezago educativo en México Blog CONEVAL. *Blog CONEVAL*. Retrieved May 27, 2025, from <http://blogconeval.gob.mx/wordpress/index.php/2022/01/25/panorama-del-rezago-educativo-en-mexico/>
- CONEVAL. Consejo Nacional de Evaluación de la Política de Desarrollo Social. (2022b). *Informe de pobreza y evaluación 2022 - Oaxaca*. Retrieved May 27, 2025, from https://www.coneval.org.mx/coordinacion/entidades/Documents/Informes_pobreza_evaluacion_2022/Oaxaca.pdf
- Damor, P. R. (2024). Anthropocene: Human activity impact on the climate and environment. *Journal of Climate Change*, 10(1), 43–45. <https://doi.org/10.3233/jcc240006>
- De la Rosa, Y. (2021, April 23). Aunque los incendios forestales aumentan, le recortan presupuesto a la CONAFOR. *Forbes México*. Retrieved May 27, 2025, from

- <https://www.forbes.com.mx/aunque-los-incendios-forestales-aumentan-le-recortan-presupuesto-a-la-conafor/>
- Delgado Ramos, G. C. (2019). *Asentamientos Urbanos Sustentables y Resilientes: Retos y Oportunidades para la Transformación Urbana en California y Baja California*; CEIICH-UNAM. Retrieved May 27, 2025, from <https://ru.ceiich.unam.mx/handle/123456789/3806>
- Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., Larigauderie, A., Adhikari, J. R., Arico, S., Báldi, A., Bartuska, A., Baste, I. A., Bilgin, A., Brondizio, E., Chan, K. M., Figueroa, V. E., Duraiappah, A., Fischer, M., Hill, R., Koetz, T., Leadley, P., Lyver, P., Mace, G. M., Martín-Lopez, B., Okumura, M., Pacheco, D., Pascual, U., Pérez, E. S., Reyes, B., Roth, E., Saito, O., Scholes, R. J., Sharma, N., Tallis, H., Thaman, R., Watson, R., Yahara, T., Hamid, Z. A., Akosim, C., Al-Hafedh, Y., Allahverdiyev, R., Amankwah, E., Asah, S. T., Asfaw, Z., Bartus, G., Brooks, L. A., Caillaux, J., Dalle, G., Darnaedi, D., Erpul, G., Escobar-Eyzaguirre, P., Failler, P., Fouda, A. M. M., Fu, B., Gundimeda, H., Hashimoto, S., Homer, F., Lavorel, S., Lichtenstein, G., Mala, W. A., Mandivenyi, W., Matczak, P., Mbizvo, C., Mehrdadi, M., Metzger, J. P., Mikissa, J. B., Moller, H., Mooney, H. A., Mumby, P., Nagendra, H., Nesshover, C., Oteng-Yeboah, A. A., Pataki, G., Roué, M., Rubis, J., Schultz, M., Smith, P., Sumaila, R., Takeuchi, K., Thomas, S., Verma, M., Yeo-Chang, Y., & Zlatanova, D. (2015). The IPBES Conceptual Framework — connecting nature and people. *Current Opinion in Environmental Sustainability*, 14, 1–16. <https://doi.org/10.1016/j.cosust.2014.11.002>
- Elsawah, S., Hamilton, S. H., Jakeman, A. J., Rothman, D., Schweizer, V., Trutnevte, E., Carlsen, H., Drakes, C., Frame, B., Fu, B., Guivarch, C., Haasnoot, M., Kemp-Benedict, E., Kok, K., Kosow, H., Ryan, M., & Van Delden, H. (2020). Scenario processes for socio-environmental systems analysis of futures: A review of recent efforts and a salient research agenda for supporting decision making. *The Science of the Total Environment*, 729, 138393. <https://doi.org/10.1016/j.scitotenv.2020.138393>
- FAO. Food and Agriculture Organization of the United Nations. (2012). The State of food and agriculture. Retrieved June 4, 2025, from <https://www.fao.org/4/i3028e/i3028e.pdf>
- FAO. Food and Agriculture Organization of the United Nations. (2018). *Global forest resources assessment 2020: Terms and definitions (FRA 2020)* (Forest Resources Assessment Working Paper No. 188). <https://www.fao.org/3/I8661EN/i8661en.pdf>
- FAO. Food and Agriculture Organization of the United Nations. (2019). El sistema alimentario en México: Oportunidades para el campo mexicano en la Agenda 2030 de Desarrollo Sostenible. Retrieved May 27, 2025, from <https://openknowledge.fao.org/handle/20.500.14283/ca2910es>
- Ferreira-Guerrero, E., Báez-Saldaña, R., Trejo-Valdivia, B., Ferreyra-Reyes, L., Delgado-Sánchez, G., Chilián-Herrera, O. L., Mendoza-Alvarado, L. R., & García-García, L. (2013). Infecciones respiratorias agudas en niños y signos de alarma identificados por padres y cuidadores en México. *Salud Pública de México*, 55(Supl 2), S307–S313.
- Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2004). Resilience and sustainable development: Building adaptive capacity in a world of transformations. *Ambio*, 33(4), 353–366. <https://doi.org/10.1579/0044-7447-31.5.437>
- Fonseca, L. M., Quadra, G. R., Paranaíba, J., Pimentel, O. a. L. F., Cotner, J., & Amado, A. M. (2022). Human impacts on aquatic ecosystems from the lens of ecological stoichiometry. *Oecologia Australis*, 26(2), 187–198. <https://doi.org/10.4257/oeco.2022.2602.08>
- Gallopin, G. C. (2006). Los Indicadores de desarrollo Sostenible: Aspectos Conceptuales y Metodológicos, Ponencia realizada para el Seminario de Expertos sobre Indicadores de Sostenibilidad en la Formulación y Seguimiento de Políticas. FAO-Fodepal.
- Gonzalez-Navarro, M., & Quintana-Domeque, C. (2016). Paving streets for the poor: Experimental analysis of infrastructure effects. *The Review of Economics and Statistics*, 98(2), 254–267. https://doi.org/10.1162/REST_a_00553
- Hanes, R. J., Bakshi, B. R., & Gopalakrishnan, V. (2018). Including nature in the food-energy-water nexus can improve sustainability across multiple ecosystem services. *Resources, Conservation and Recycling* 137, 214–228. <https://doi.org/10.1016/j.resconrec.2018.06.003>
- Hurst, P., Termine, P., & Karl, M. (2007). *Trabajadores Agrícolas y su Contribución a la Agricultura y el Desarrollo Rural Sostenibles*. FAO-OIT-UITA. Retrieved May 27, 2025, from

- <https://openknowledge.fao.org/server/api/core/bitstreams/c5b7cb05-87a7-4e30-8917-4d893e3b0b26/content>
- Ibáñez Pérez, R. M. (2012). Indicadores de sustentabilidad: utilidad y limitaciones. *Teoría y Praxis*, 8(11), 102–126. <https://doi.org/10.22403/uqroomx/typ11/0>
- IBRD. International Bank for Reconstruction and Development / The World Bank. (2021). *Strengthening the link between economic growth and poverty reduction in Mali: A poverty assessment*. Retrieved May 25, 2025, from <https://documents1.worldbank.org/curated/en/162321637060653974/pdf/Strengthening-the-Link-between-Economic-Growth-and-Poverty-Reduction-in-Mali-A-Poverty-Assessment.pdf>
- IMT. Instituto Mexicano del Transporte. (2022). *Red Nacional de Caminos. gob.mx*. Retrieved May 25, 2025, from <https://www.gob.mx/imt/acciones-y-programas/red-nacional-de-caminos>
- Inchauste Comboni, M. G., Isik-Dikmelik, A., Rodríguez Chamussy, L., Cadena Kotsubo, K. E., Jaén Torres, M. P., Ávila Parra, C., Steta Gándara, M. C., Miñoso, M. del C., Gutiérrez de Díaz, Y., Sarrabayrouse, M., Londoño Aguirre, D. I., González, D. D., & Islas Orduño, D. O. (2021). *La participación laboral de la mujer en México*. World Bank Group. <https://documents.worldbank.org/en/publication/documents-reports/documentdetail/753451607401938953>
- INEGI. Instituto Nacional de Estadística y Geografía. (2022). *Estadísticas de Defunciones Registradas 2021*. Retrieved May 25, 2025, from https://www.inegi.org.mx/contenidos/saladeprensa/boletines/2022/dr/dr2021_07.pdf
- INEGI. Instituto Nacional de Estadística, Geografía e Informática. (2000). *Indicadores de Desarrollo Sustentable en México*. Retrieved May 25, 2025, from https://www.inegi.org.mx/contenidos/productos/prod_serv/contenidos/espanol/bvinegi/productos/historicos/2104/702825168124/702825168124_1.pdf
- INEGI. Instituto Nacional de Geografía y Estadística. (2020). *PIB por Entidad Federativa (PIBE). Base 2013*. Retrieved May 25, 2025, from <https://www.inegi.org.mx/programas/pibent/2013/>
- INEGI. Instituto Nacional de Geografía y Estadística. (2022). *Censo Nacional de Gobiernos Municipales y Demarcaciones Territoriales de la Ciudad de México 2019 Información relevante: enfermedades diarreicas agudas*. Dirección General de Epidemiología (DGE). Secretaría de Salud. Retrieved May 27, 2025, from <https://www.inegi.org.mx/programas/cngmd/2019/#documentacion>
- INMUJERES. Instituto de las Mujeres. (2022). *Sistema de Indicadores de Género*. Retrieved May 25, 2025, from http://estadistica.inmujeres.gob.mx/formas/panorama_general.php?menu1=8&IDTema=8&pag=1
- IPBES. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. (2019). *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services*. IPBES Secretariat. <https://doi.org/10.5281/zenodo.3553579>
- Leviston, Z., Walker, I., Green, M., & Price, J. (2018). Linkages between ecosystem services and human wellbeing: A Nexus Webs approach. *Ecological Indicators*, 93, 658–668. <https://doi.org/10.1016/j.ecolind.2018.05.052>
- López Calva, L. F., & Vélez Grajales, R. (2003). El concepto de desarrollo humano, su importancia y aplicación en México. *Estudios sobre Desarrollo Humano PNUD México* No. 2003-1. PNUD. Retrieved May 25, 2025, from <https://sic.cultura.gob.mx/documentos/1007.pdf>
- Lustig, N. (2007). Salud y desarrollo económico. El caso de México. *El Trimestre Económico*, 74(296), 793–822. http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S2448-718X2007000400793&lng=es&tlng=es.
- McPhearson, T., Pickett, S. T. A., Grimm, N. B., Niemelä, J., Alberti, M., Elmqvist, T., Weber, C., Haase, D., Breuste, J., & Qureshi, S. (2016). Advancing Urban Ecology toward a Science of Cities. *BioScience*, 66(3), 198–212. <https://doi.org/10.1093/biosci/biw002>
- Medina, A. (2020, August 27). México invierte 2.5% del PIB en Salud, cuando lo ideal sería 6% (o más): OPS. *Forbes México*. Retrieved May 25, 2025, from <https://www.forbes.com.mx/revista-empresa-mexico-invierte-2-5-del-pib-en-salud-cuando-lo-ideal-seria-6-o-mas-ops/>
- Nagarajan, R., Scutari, M., & Lèbre, S. (2013). *Bayesian Networks in R: with Applications in Systems Biology* Springer.

- OECD. Organisation for Economic Co-operation and Development. (1993). *OECD core set of indicators for environmental performance reviews: A synthesis report by the Group on the State of the Environment* (Environment Monographs No. 83). OECD Publishing. [https://one.oecd.org/document/OCDE/GD\(93\)179/en/pdf](https://one.oecd.org/document/OCDE/GD(93)179/en/pdf)
- OECD. Organisation for Economic Co-operation and Development. (1999). *Environmental Indicators for Agriculture: Volume 1 – Concepts and Framework*. Retrieved May 25, 2025, from https://www.oecd.org/content/dam/oecd/en/publications/reports/1999/09/environmental-indicators-for-agriculture_g1gh1797/9789264173873-en.pdf
- Olaiz-Fernández, G. A., Gómez-Peña, E. G., Juárez-Flores, A., Anda, F. J. V., Morales-Ríos, J. E., & Carrasco, O. F. (2019). Panorama histórico de la enfermedad diarreica aguda en México y el futuro de su prevención. *Salud Pública de México*, 62(1), 25–35. <https://doi.org/10.21149/10002>
- OMS. Organización Mundial de la Salud. (2018, October 29). *Más del 90% de los niños del mundo respiran aire tóxico a diario*. Retrieved May 25, 2025, from <https://www.who.int/es/news/item/29-10-2018-more-than-90-of-the-world%E2%80%99s-children-breathe-toxic-air-every-day#:~:text=La%20contaminaci%C3%B3n%20del%20aire%20afecta,a%20niveles%20bajos%20de%20exposici%C3%B3n>
- ONU. Organización de las Naciones Unidas. (2011). *Impacto del VIH/SIDA en la educación y la pobreza*. Retrieved May 25, 2025, from <https://www.un.org/es/chronicle/article/impacto-del-vih-sida-en-la-educacion-y-la-pobreza>
- Ostrom, E. (2009). A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science*, 325(5939), 419–422. <https://doi.org/10.1126/science.1172133>
- Pérez Mesa, J. C., (2008). Factores relevantes en la medición de la pobreza y el desarrollo humano: índices PNUD. *Revista de Economía Mundial*, (19), 183–197.
- PNUD. Programa de las Naciones Unidas para el Desarrollo (2015). *Informe sobre Desarrollo Humano 2015*. Retrieved May 25, 2025, from <https://www.undp.org/es/publicaciones/informe-sobre-desarrollo-humano-2015>
- Polido, A. (2023). The role of Strategic Environmental Assessment for Sustainability in Urban Systems Transformation. In *Palgrave studies in sub-national governance* (pp. 181–195). https://doi.org/10.1007/978-3-031-20577-4_9
- R Core Team. (2024). *R: A language and environment for statistical computing*. Version 4.x. R Foundation for Statistical Computing. <https://www.r-project.org/>
- Ramos, T. B. (2019). Sustainability assessment: Exploring the frontiers and paradigms of indicator approaches. *Sustainability*, 11(3), 824. <https://doi.org/10.3390/su11030824>
- Rivera, J. A., Barquera, S., González-Cossío, T., Olaiz, G., & Sepúlveda, J. (2004). Nutrition transition in Mexico and in other Latin American countries. *Nutrition Reviews*, 62(s2), S149–S157. <https://doi.org/10.1111/j.1753-4887.2004.tb00086.x>
- Rojas, R. (2017, May 4). Aumentan enfermedades diarreicas por altas temperaturas en Zacatecas. *Saludiarario*. Retrieved May 25, 2025, from <https://www.saludiarario.com/por-altas-temperaturas-aumentan-enfermedades-diarreicas-en-zacatecas/>
- SADER. Secretaría de Agricultura y Desarrollo Rural. (2016). *Tipos de Cultivo, Estacionalidad y Ciclos*. gob.mx. Retrieved May 25, 2025, from <https://www.gob.mx/agricultura/es/articulos/tipos-de-cultivo-estacionalidad-y-ciclos>
- SADER. Secretaría de Agricultura y Desarrollo Rural. (2022). *Acuicultura en México*. Retrieved May 25, 2025, from <https://www.gob.mx/agricultura/articulos/acuicultura-en-mexico?idiom=es#:~:text=La%20producci%C3%B3n%20acu%C3%ADcola%20en%20M%C3%A9xico,los%20cuales%20el%2070%25%20de>
- Sambo, B., Sperotto, A., Torresan, S., Pittore, M., Zebisch, M., & Critto, A. (2024). Looking at the Water-Energy-Food nexus through the lens of Ecosystem Services: A new perspective. *Environmental Research Letters*, 19, 121003. <https://doi.org/10.1088/1748-9326/ad96cf>
- Sarkki, S. (2017). Governance services: Co-producing human well-being with ecosystem services. *Ecosystem Services*, 27, 82–91. <https://doi.org/10.1016/j.ecoser.2017.08.003>
- Sarkki, S., Ficko, A., Grunewald, K., Kyriazopoulos, A. P., & Nijnik, M. (2016). How pragmatism in environmental science and policy can undermine sustainability transformations: the case of

- marginalized mountain areas under climate and land-use change. *Sustainability Science*, 12(4), 549–561. <https://doi.org/10.1007/s11625-016-0411-3>
- Schlüter, M., Orach, K., Lindkvist, E., Martin, R., Wijermans, N., Bodin, Ö., & Boonstra, W. J. (2019). Toward a methodology for explaining and theorizing about social-ecological phenomena. *Current Opinion in Environmental Sustainability*, 39, 44–53. <https://doi.org/10.1016/j.cosust.2019.06.011>
- Schuschny, A., & Soto, H. (2009). *Guía metodológica. Diseño de indicadores compuestos de desarrollo sostenible*. CEPAL. Retrieved May 25, 2025, from http://repositorio.cepal.org/bitstream/handle/11362/36611/S2009230_es.pdf.
- Scutari, M., & Denis, J. (2021). *Bayesian Networks with Examples in R*, 2nd edition. Chapman and Hall, Boca Raton.
- SEMARNAT & CONAGUA. Secretaría de Medio Ambiente y Recursos Naturales & Comisión Nacional del Agua. (2019). *Estadísticas agrícolas de los distritos agrícolas, 2017-2018* (1st ed., Vol. 1). Retrieved May 25, 2025, from https://files.conagua.gob.mx/conagua/publicaciones/Publicaciones/EADR_2017-18.pdf
- SEMARNAT. Secretaría de Medio Ambiente y Recursos Naturales. (2021). *Programa Especial de Cambio Climático 2021-2024*. Gobierno de México. Retrieved May 25, 2025, from https://www.gob.mx/cms/uploads/attachment/file/685848/SEMARNAT_081121_EV.PDF
- Shi, Y., Zhai, G., Xu, L., Zhou, S., Lu, Y., Liu, H., & Huang, W. (2021). Assessment methods of urban system resilience: From the perspective of complex adaptive system theory. *Cities*, 112, 103141. <https://doi.org/10.1016/j.cities.2021.103141>
- Shivanna, K. R. (2022). Climate change and its impact on biodiversity and human welfare. *Proceedings of the Indian National Science Academy*, 88, 160–171. <https://doi.org/10.1007/s43538-022-00073-6>
- Smeets, E., & Weterings, R. (1999). *Environmental indicators: Typology and overview. Technical Report No. 25*. European Environment Agency. Retrieved May 25, 2025, from <https://www.eea.europa.eu/en/analysis/publications/tec25>
- SNIARN & SEMARNAT. Sistema Nacional de Información Ambiental y de Recursos Naturales & Secretaría de Medio Ambiente y Recursos Naturales. (2024). *Sistema Nacional de Información Ambiental y de Recursos Naturales*. Gobierno de México. Retrieved May 25, 2025, from <https://www.gob.mx/semarnat/acciones-y-programas/sistema-nacional-de-informacion-ambiental-y-de-recursos-naturales>
- SNIARN. Sistema Nacional de Información Ambiental y de Recursos Naturales (2012). *Informe del Medio Ambiente*. Retrieved May 25, 2025, from <https://apps1.semarnat.gob.mx:8443/dgeia/informe15/tema/cap7.html>
- Soto-Mora, C. (2003). La agricultura comercial de los distritos de riego en México y su impacto en el desarrollo agrícola. *Investigaciones Geográficas*, (50), 173–195. http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S0188-46112003000100016&lng=es&tng=es
- Tapia, G. L. A., & Valenti, G. (2016). Desigualdad educativa y desigualdad social en México. Nuevas evidencias desde las primarias generales en los estados. *Perfiles Educativos*, 38(151), 32–54. <https://doi.org/10.22201/iisue.24486167e.2016.151.54885>
- Turner, B. L., Lambin, E. F., & Reenberg, A. (2016). The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences*, 104(52), 20666–20671. <https://doi.org/10.1073/pnas.0704119104>
- UN. United Nations. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development*. Retrieved May 25, 2025, from <https://sdgs.un.org/2030agenda>
- UNAIDS. Joint United Nations Programme on HIV/AIDS. (2011). *Global HIV/AIDS response: Epidemic update and health sector progress towards universal access – Progress report 2011*. Retrieved May 25, 2025, from https://www.unaids.org/sites/default/files/media_asset/20111130_UA_Report_en_1.pdf
- UNDP. United Nations Development Programme. (2015). *Human Development Report 2015: Work for Human Development*. Retrieved May 25, 2025, from <https://hdr.undp.org/system/files/documents/global-report-document/2015humandevlopmentreport1.pdf>

- UNFCCC. United Nations Framework Convention on Climate Change. (2022). *Dimensions and examples of the gender-differentiated impacts of climate change, the role of women as agents of change and opportunities for women*. Synthesis report by the Secretariat. Retrieved May 25, 2025, from <https://unfccc.int/documents/494455>
- UNFPA. Fondo de Población de las Naciones Unidas. (2018a). *Salud y mortalidad materna de las mujeres indígenas*. Retrieved May 25, 2025, from <https://www.unfpa.org/es/resources/salud-y-mortalidad-materna-de-las-mujeres-indigenas>
- UNFPA. United Nations Population Fund. (2018b). *The Maternal Health Thematic Fund: Annual Report 2017 and Review of Phase II (2014–2017)*. Retrieved May 25, 2025, from https://www.unfpa.org/sites/default/files/pub-pdf/UNFPA_PUB_2018_EN_MHTF_AnnualReport2017.pdf
- UNSTATS. United Nations Statistics Division. (2017). *SDG Indicators — SDG Indicators*. Retrieved May 25, 2025, from <https://unstats.un.org/sdgs/indicators/indicators-list/>
- Valle-Jones, D. (2022). *mxmaps: Create Maps of Mexico*. <https://www.diegovalle.net/mxmaps/>
- Vázquez-Valencia, R. A., & García-Almada, R. M. (2018). Indicadores PER y FPEIR para el análisis de la sustentabilidad en el municipio de Cihuatlán, Jalisco, México. *Noesis. Revista de Ciencias Sociales*, 27(53-1), 1–26. <https://doi.org/10.20983/noesis.2018.3.1>
- Vega, A. (2022, January 20). Bosques más vulnerables a plagas: Un efecto del cambio climático que ya se observa en México. *Mongabay Latam*. Retrieved May 27, 2025, from <https://es.mongabay.com/2022/01/bosques-mas-vulnerables-a-plagas-un-efecto-del-cambio-climatico-mexico/>
- Waas, T., Hugé, J., Block, T., Wright, T., Benitez-Capistros, F., & Verbruggen, A. (2014). Sustainability assessment and indicators: Tools in a decision-making strategy for sustainable development. *Sustainability*, 6(9), 5512–5534. <https://doi.org/10.3390/su6095512>
- Wang, X., Song, C., Cheng, C., Ye, S., & Shen, S. (2021). Cross-national perspectives on using Sustainable Development Goals (SDGs) indicators for monitoring sustainable development: A database and analysis. *Chinese Geographical Science* 31(4), 600–610. <https://doi.org/10.1007/s11769-021-1213-9>
- Warren, K., Franklin, C., & Streeter, C. L. (1998). New Directions in Systems Theory: Chaos and Complexity. *Social Work*, 43(4), 357–372. <https://doi.org/10.1093/sw/43.4.357>
- Yin, C., Zhao, W., Cherubini, F., & Pereira, P. (2021). Integrate ecosystem services into socio-economic development to enhance achievement of sustainable development goals in the post-pandemic era. *Geography and Sustainability*, 2(1), 68–73. <https://doi.org/10.1016/j.geosus.2021.03.002a>
- Yuan, M.-H., & Lo, S.-L. (2020). Ecosystem services and sustainable development: Perspectives from the food-energy-water Nexus. *Ecosystem Services*, 46, 101217. <https://doi.org/10.1016/j.ecoser.2020.101217>
- Zepeda-Ortega, I. E., Ángeles-Castro, G., & Carrillo-Murillo, D. G. (2019). Infraestructura carretera y crecimiento económico en México. *Problemas del Desarrollo*, 50(198), 145–168. <https://doi.org/10.22201/iiec.20078951e.2019.198.66383>