Sustainability Science
https://doi.org/10.1007/s11625-025-01641-7

ORIGINAL ARTICLE

Sustainability assessment and intervention scenarios in a transnational watershed socioenvironmental system

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Received: 30 October 2023 / Accepted: 16 January 2025

Abstract

The assessment of the sustainability status of territories is a prerequisite for the development of public policy strategies to be implemented on them aimed at attaining established sustainability goals. A socioenvironmental systems perspective, in which economic, social and environmental aspects constituting these territories and their interactions between them are considered, allows for a comprehensive analysis of the dynamics of these systems. Given the complexity of such systems, sets of indicators are required to simplify and quantify them. Here, we developed a model of the dynamics of the socioenvironmental system associated with the Usumacinta River basin (URB), a 77,000 km^2 area shared by Guatemala and Mexico. We fed this model with information from a system of 51 sustainability indicators and modeled the relationships between these indicators, as well as developed indices to visualize the sustainability status of these components. This allowed us to evaluate the impact of different scenarios of change in the indicators of public policy on the entire URB system. We determine that the URB displays a good state of its natural component and of the impact human activities have in the territory; however, components associated with the human activities themselves, their drivers, the social condition and the human assets displayed differences in their sustainability status between countries. Concerning the evaluation of scenarios of changes in the magnitude of the public policy indicators, we established that Ecosystem Services payment increases the overall sustainability of the territory. We conclude that both environmental protection and social investment should be considered if socioenvironmental sustainability is to be attained.

Keywords Socioenvironmental model · Socioenvironmental system · Sustainability indicators · Sustainability indices · River basin · Usumacinta River

Introduction

Over the last decade, a large body of literature has shown that human well-being closely relates to the global state of the environment because of the multiple relationships that we establish with it as individuals and society (Ghermandi and Sinclair 2019; Hansson et al. 2019; Li et al. 2022; Spano et al. 2020). However, one of the great concerns humanity is facing is its development in its different dimensions, environmental, economic and social, in a globalized world where there is great demand from markets, exploitation of resources and social inequality (Beumer et al. 2018; Feng et al. 2023; Olawumi and Chan 2018).

Development that meets the needs of present generations without compromising the ability of future generations to meet their own needs is the goal of sustainable development (Brundtland et al. 1987). If we understand sustainability as

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Handled by Herlin Chien, National Pingtung University of Science and Technology (NPUST), Taiwan.

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the characteristic of a process or state that can be maintained indefinitely, sustainable development aims to achieve human development that is maintained over time without degrading the ecosystems and the services they provide (Ben-Eli 2018; Ruggerio 2021).

Sustainable development has been discussed in terms of three components: economic, environmental and social (Boulanger 2008; Cavagnaro and Curiel 2022; James et al. 2015). Economically, the aim is to grow and to alleviate poverty. Socially, the aim is to provide quality of life for current generations and to guarantee that future generations have the same or greater access to social resources. Environmentally, the aim is to preserve the integrity of ecosystems and biological diversity (Cavagnaro and Curiel 2022; Haro-Martínez and Taddei-Bringas 2014; Kreisel 2018). Addressing the issue of sustainability requires an approach that integrates these three aspects: the socioenvironmental system. A socioenvironmental system is a complex system, where environmental, social and economic agents interact on multiple temporal and spatial scales (Holling 2001; Ostrom 1998). Examples of socioenvironmental systems are hydrographic basins, land surfaces drained and articulated by a continuous and well-defined hydrological system whose waters flow into other water bodies, and whose geographic limits are generally determined by water (Challenger et al. 2014; Ensley et al. 2021).

From the above, we can see sustainability as an emerging property of the dynamics of a socioenvironmental system, and to understand this property we need not only to describe the components of the system, but the way in which they interrelate and generate causal interactions (Dijk et al. 2017; Galanina et al. 2017; Gomez-Jaramillo et al. 2023; Nicholls et al. 2016). In this way, we approach sustainability in a holistic manner, understanding the impact of public policies over the entire socioecosystem (Castillo et al. 2014; Gomez-Jaramillo et al. 2023); i.e., we follow a system thinking of sustainability (Sanneh 2018).

Given the inherent complexity of a socioenvironmental system, its direct observation and measurement are impossible and tools are required to approach its different aspects and relations. An option is to use sustainability indicators, which allow measuring the trend the system is following in terms of sustainability (Gomez-Jaramillo et al. 2023; López et al. 2008; Martinez-Fernandez et al. 2021; Quiroga 2007). By conceptualizing phenomena and highlighting trends and interactions, indicators simplify, quantify, structure, analyze and communicate complex information (Alaimo and Maggino 2020; Alaimo et al. 2021; Pissourios 2013; Wu 2013), and are designed to have standards against which to evaluate, estimate or demonstrate progress of policy actions with respect to established sustainability goals (Brugmann 2021).

In the present work, we assess the sustainability status of the socioenvironmental system associated with the Usumacinta River basin (URB). We implement an analytic model describing the relationships between components of a socioenvironmental system, gather a set of sustainability indicators proposed by different programs and construct indices for each component of the system. To feed these indicators and indices, we assemble available, comparable information provided by national agencies from the two main countries where the URB lies, Mexico and Guatemala, as well as from international institutions. With this information, we visualized its spatial heterogeneity via a geoweb application (http://idegeo.centrogeo.org.mx/ms/simula), evaluated the sustainability status of the URB and explored different scenarios of public policy intervention to determine their impact on the sustainability of the entire socioecosystem.

Methods

Study site

The Usumacinta River basin (URB) has an area of 77,436 km^2, shared between Guatemala (55.75%), Mexico (44.21%) and Belize (0.04%), and constitutes a unique site in Mesoamerica for its natural and cultural heritage (Saavedra et al. 2019). The URB is a complex hydrological system of rivers streams and rivers that originate in the mountains of Guatemala and in the state of Chiapas in Mexico, and converge in the Usumacinta River, which is joined by the Grijalva River before it flows into the Gulf of Mexico. Likewise, a branch of the Usumacinta separates before this mouth and becomes the San Pedro and San Pablo rivers.

The URB has a large topographic, geological and climatic heterogeneity (Saavedra et al. 2019), which allows the presence of a great number of vegetation types (Meave et al. 2021) and high vascular and vertebrate diversities (Jiménez-López et al. 2023; Charruau et al 2019).

About 3.5 million people live in the URB, 2.3 million in 45 municipalities in six Guatemalan departments (Petén, Huehuetenango, Quiche, Totonicapán, Alta Verapaz and Baja Verapaz) and 1.2 million in 21 municipalities in the states of Campeche, Chiapas and Tabasco in Mexico. Forty percent of the population is highly marginalized and the internal inequalities within the URB are very contrasting. The majority of the territory is rural, with a large dispersion of small towns (Soares and García-García 2018).

Economically, the main productive activity is agriculture. Livestock raising is extensive and requires a large amount of land per livestock unit, which has resulted in high deforestation rates (Gallardo-Cruz et al. 2021). Forestry is not developed in the URB and fisheries only in the lower URB with a high impact on the ecosystem, as it is generally carried out without control or regulation.

Recently, tourism and ecotourism activities have been promoted in different areas of the URB, mainly around archaeological zones and in the surrounding of protected natural areas (de la Maza et al. 2015).

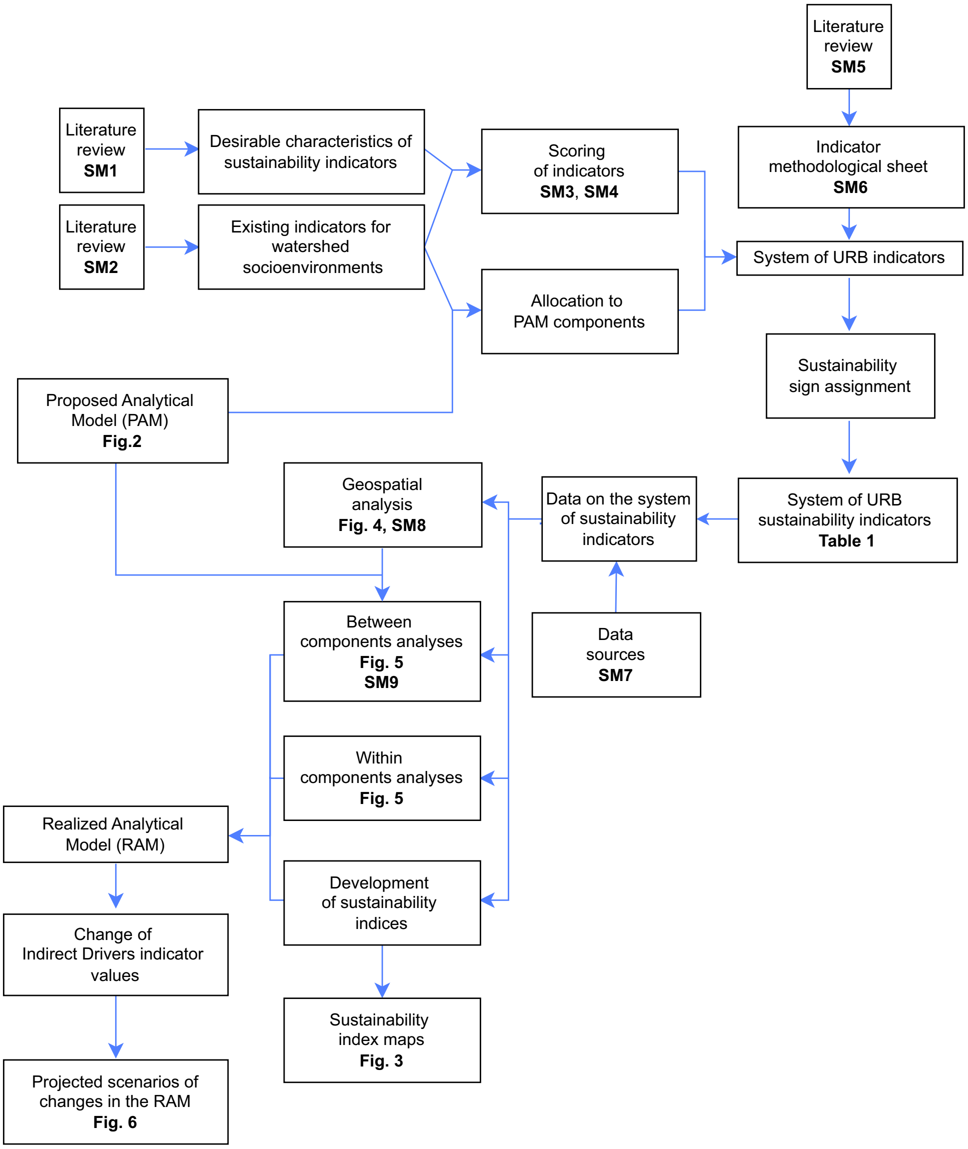
The URB offers invaluable ecosystem services, such as the provision of fresh water, nutrients for the fisheries in the Gulf of Mexico, carbon sequestration in wetlands and forest stands, climate and nutrient regulation, and a multitude of species used for multiple purposes.

For the study of the URB from a socioenvironmental systems perspective, to integrate a system of sustainability indicators and to evaluate the impact of different scenarios of change in the indicators of public policy, we followed a procedure summarized in Fig. 1 and described in the following sections.

Analytical model

To describe, in a systemic way, the short-term dynamics of the socioenvironment associated with the URB, we used an analytical model proposed (PAM) by MZ and collaborators for this particular system (Fig. 2; CCGS 2019). Starting with the model developed by the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES; Díaz et al. 2015), a model of the interactions between nature and people most relevant to IPBES's focus on sustainability, the authors iteratively developed the PAM through team discussions and repeated trials of application to case studies. The final model represents, in a simplified and measurable way, the complexity of the URB's functioning, including its social and environmental aspects, the impacts of human activities, and their drivers, and the ecosystem services that their interaction entails,

Fig. 1 Flow diagram of the procedure followed in this study. The table, supplementary materials and the rest of the figures are in bold



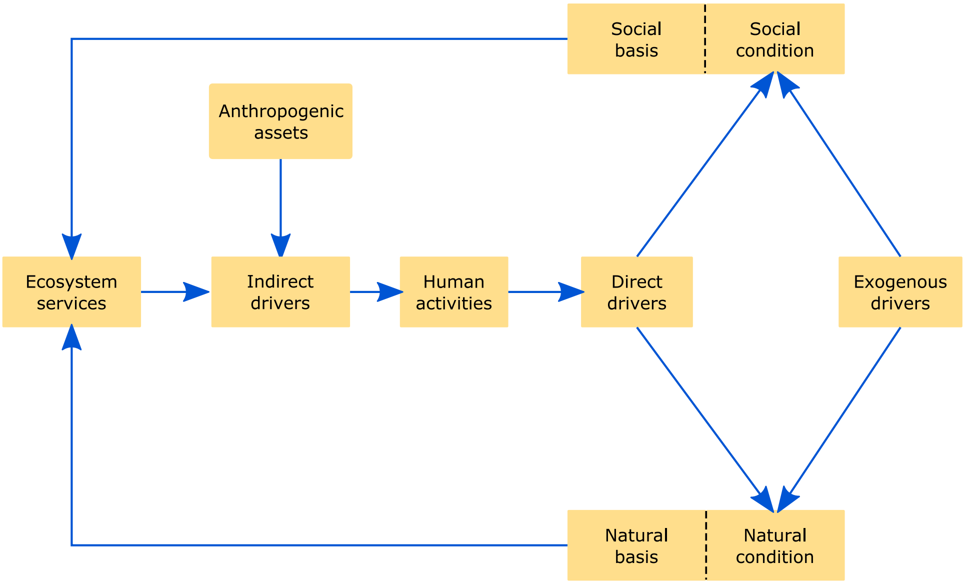


Fig. 2 Proposed analytical model of the socioenvironmental system of the Usumacinta River basin. The direction of the relationships is the interaction between the components (modified from CCGS 2019). See definition of components in "Analytical model" in Methods

as well as the feedback nature of its functioning. In this way, the PAM aims at facilitating the understanding and communication between different knowledge areas, as well as the identification of the relevance of each of these areas to address socioenvironmental issues.

The nine components of the PAM are (Fig. 2):

1. *Indirect Drivers*, ways in which societies organize themselves and their interactions with nature, which can be modified through changes in public policy.
2. *Human Activities*, productive or non-productive activities that take place in a territory that define the state and use of natural resources and are regulated by the Indirect Drivers.
3. *Exogenous Drivers*, events or circumstances that do not originate or cannot be explained by the Human Activities, but that affect the characteristics of Nature and/or Nature, attributes that characterize nature's status, subdivided into Basal and Condition attributes to differentiate between those that determine the Ecosystem Services and are directly affected by the Direct and Exogenous Drivers from those that do not directly determine the Ecosystem Services and are not directly affected by these Drivers.
4. *Society*, attributes that characterize the level of well-being of a society and the quality of life of a population, with the same subdivisions of Basal and Condition attributes.
5. *Ecosystem Services*, benefits that humans receive from nature.
6. *Direct Drivers*, processes generated as a consequence of the activities in the territory and that generate a process of change in nature and society, such as deforestation, degradation, pollution or resource depletion.
7. *Indirect Drivers*, ways in which societies organize themselves and their interactions with nature, which can be modified through changes in public policy.
8. *Exogenous Drivers*, events or circumstances that do not originate or cannot be explained by the activities carried out in the territory, but that affect the characteristics of society and/or nature.
9. *Anthropogenic Assets*, those produced by human societies that do not depend directly on nature.

Integration of a system of sustainability indicators

To assess the PAM in the URB, we defined a set of sustainability indicators that served as proxies to each of the PAM components. Firstly, we performed a literature review on the qualitative and quantitative techniques for selecting diagnostic indicators of a system's state and change factors. Based on this literature review (SM1), we identified the desirable characteristics in a sustainability indicator: (1) be freely available from public sources for each country, (2) possess an adequate spatial scale of analysis, which, for this study, was the municipality, (3) already include several measurements over time that would increase the probability of its continuity through time and (4) have a high thematic precision, which refers to the degree of overlap between the thematic content of the information sources and the thematic content addressed by the indicators. These characteristics cover the criteria of relevance, analytic soundness, measurability, statistical viability and internal consistency proposed by several authors (OECD 1993; Guttman et al. 2004; Fernandes and Woodhouse 2008; Quiroga 2009).

Secondly, we perform a literature review on the sustainability/ecological indicators proposed for the monitoring of similar systems. With this review, we integrated a list of indicators proposed by different institutions and organizations (Source column in SM2), both at the national and international level.

Thirdly, we used the desirable characteristics to assign a score to each indicator. Most of the characteristics had the same score; however, we assigned a higher score to the geographic disaggregation characteristic, since a good spatial resolution was desired. For each PAM component, we ended up with at least one indicator.

Fourthly, we assigned a positive or negative sign to each indicator if its increase either improved or reduced the sustainability of the socioenvironmental system. Although all indicators originated from sustainable development goals, some were not strictly so and thus were assigned a null sign; these were not excluded from the indicators system as they allow the diagnosis of the socioenvironmental system, but excluded from the construction of the sustainability indices (see below).

Geospatial analysis of indicators

Once the set of indicators had been identified, we analyzed them spatially. First, we determined the presence of spatial correlation in the values of each indicator through Moran's I index (range of posible values: $[-1,1]$; Anselin 1995). A positive value for this index indicates that the features are part of one or more clusters and have neighboring features with similarly high or low values; a negative value indicates that the feature is an outlier and has neighboring features with dissimilar values. In terms of system dynamics, a value far from zero, i.e., close to -1 or 1, represents a reinforcement of the differences between regions of the URB; a value close to zero relates to uncoordinated management efforts that translate into a slower improvement in the sustainability of the entire URB.

From this analysis, we then evaluated the spatial structure of the indicators by identifying clusters with similar behavior; the presence of clusters suggests socioterritorial segregation processes (Buzai 2014).

Development of sustainability indices

To integrate the information provided by the indicators associated with each PAM component into a single figure for each municipality in the region, we developed a sustainability index for each component. Thus, we first transformed the indicators to make them comparable among each other and to reflect their signs in terms of sustainability. Then, we restricted the indicator to the [0, 1] interval and reflected its sustainability sign by applying the formula:

$$x'_{jk} = (x_{jk} - \min(x_{jk}))/(\max(x_{jk}) - \min(x_{jk})), \tag{1}$$

where x_{jk} is the standardized variable, if the indicator had a positive sign; and

$$x'_{jk} = (\max(x_{jk}) - x_{jk})/(\max(x_{jk}) - \min(x_{jk})), \tag{2}$$

if the indicator had a negative sign. The index for each component was the average of the transformed indicators associated with it at the municipality level. Thus, a value of zero corresponded to the worst municipality in its sustainability of that component, and a value of one to the best one.

Finally, to guarantee the repeatability of the calculations involved in the definition of the indices and indicators, we developed a methodological sheet with the information on each selected indicator/index. This sheet was developed from a revision of 20 documents (SM5 and SM6).

Statistical analysis of the relations between and within PAM components

The analysis of the relationships between components of the PAM consisted in constructing linear mixed-effect models (Pinheiro and Bates 2000). In these models, each response variable was considered as potentially explained by all or a subset of the variables of the cause components. We included the clusters identified in the geospatial analysis as random effects to account for the spatial aggregation in the response variable. Since we wanted to identify the best predictive model, we performed model selection based on the square root of the mean squared error (RMSE) in predicting observed values of the response variable selected through a leave-one-out cross-validation procedure. The selected model was the one with the smallest RMSE.

Additionally, we evaluated the relative statistical importance of each explanatory variable in this selected model. This was done through likelihood ratio tests in which we compared this selected model with one that excluded the variable of interest.

Finally, because we also wanted to identify potential correlations between indicators within components, we performed correlation analyses between all pairs of indicators within each component using the Pearson's correlation coefficient. Correlations were considered strong if their absolute value was over 0.75.

All statistical analyses were performed in R (R Core Team 2022) using the lme4 package (Bates et al. 2015).

The analytical model that resulted from the between and within components resulted in a realized analytical model (RAM), which we used for the exploration of Indirect Drivers change scenarios.

Scenarios of indirect drivers change and their impact in the socioenvironment

Based on the RAM, we simulated the effect that a 10% improvement on an Indirect Drivers indicator would have on the rest of the components of the RAM. Thus, for each indicator of the Indirect Drivers component, we: (1) increased the original value of the Indirect Drivers indicator by 10% and (2) started a chain reaction on the rest of the components of the RAM in which, for each component, we predicted the response variable using the between-components relational models developed in the previous section, now with the modified values of the explanatory variables.

Results

The URB displayed a good state in its sustainability in its *Natural Conditions* and *Direct Drivers* components; and spatial heterogeneity, with a more sustainable territory in Mexico than in Guatemala, in its *Indirect Drivers*, *Social Condition* and *Anthropogenic Assets* components, and an opposite pattern in its Human Activities component, both at the level of the selected indicators (see the SIMULA platform) and the developed indices (Fig. 3). When exploring scenarios of improvement in the *Indirect Drivers* component indicators, we establish that only Ecosystem Services payment improves the overall sustainability of the territory.

System of sustainability indicators

For the system of indicators, a total of 20 sources were reviewed among publications and entities at the international and national levels, providing a total of 215 indicators (SM3), of which 51 indicators were considered to meet the characteristics and criteria for selection (Table 1). The number of indicators per component varied from one in *Ecosystem Services* to nine in *Social condition*. In general, the quality of the indicators for each component varied from regular to good (SM3 and SM4). Regarding the information

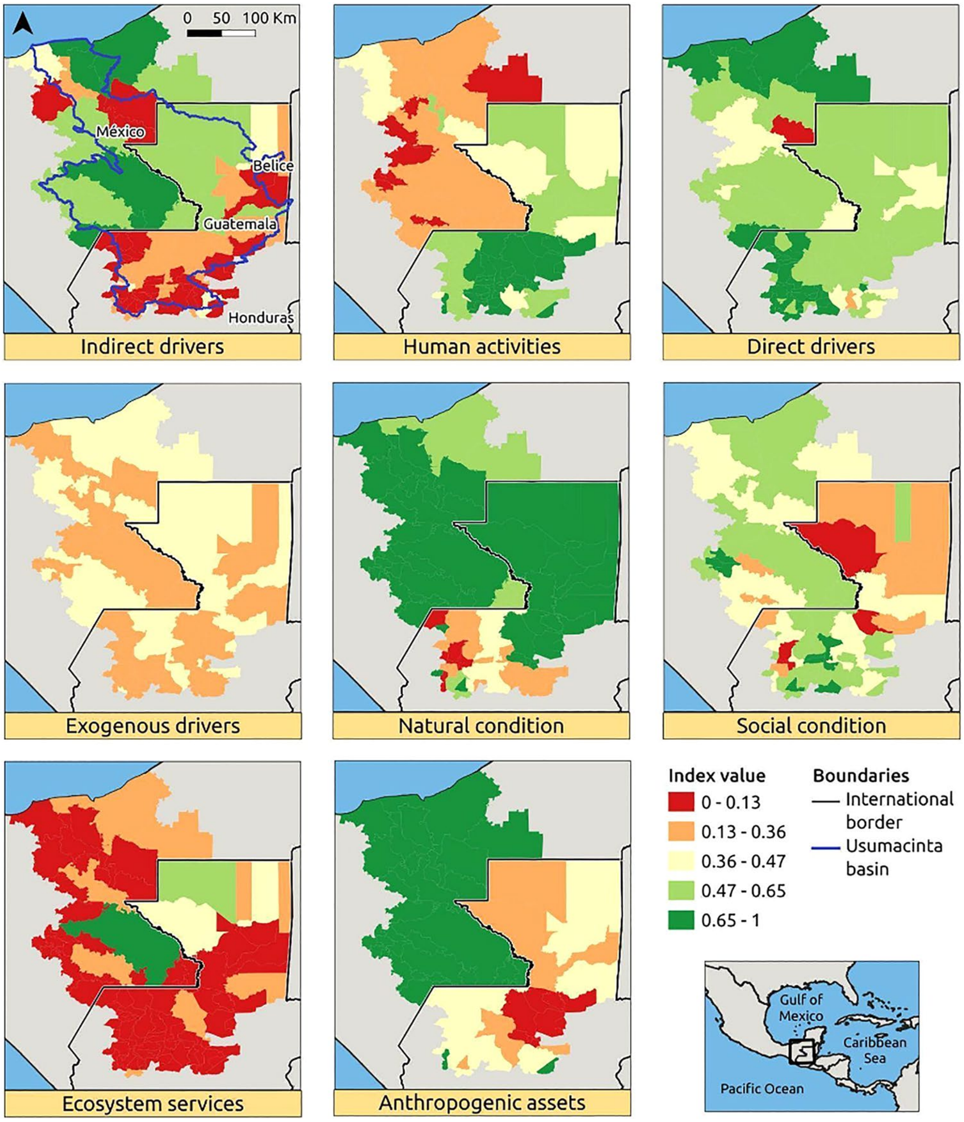


Fig. 3 Sustainability index maps for the eight components of the analytical model in the Usumacinta River basin. The index ranges on the [0,1] interval, with a value of zero reflecting the municipality in the basin with the worst sustainability status in the component, and a value of one for the municipality with the best status

sources, the public institutions involved in monitoring, registration or census programs stood out: INEGI, in Mexico, and INE, in Guatemala, generated > 50% of the indicators selected (SM7). In more than 70% of the indicators, information was obtained at the municipal level and complemented with state/department level data.

Geospatial analysis of indicators

Moran's index for the 51 selected indicators took positive values, although with variable magnitude (Fig. 4). The *Natural Conditions*, *Indirect Drivers* and *Ecosystem Services* components displayed the lowest values; however, small agglomeration patterns could be detected that reinforced subregional differentiation (SM8). The rest of the components displayed medium to high positive values of the index translating into agglomeration patterns, thus suggesting socioenvironmental differentiation in the URB, with poor conditions concentrated especially in the municipalities south of the region where indicators have their lowest values, and negatively affecting regional sustainability. Maps of the cluster maps are in SM8 along with more details on the analysis.

Relationships within and between RAM components

We found correlations between indicators within each RAM component in six of the seven components with more than one indicator, with the most numerous in Society (*Social basis* + *Social condition*; Fig. 5). Most correlations were positive (e.g., in the Nature component, *Direct Drivers*, *Indirect Drivers* and *Anthropogenic Assets*) and only in two components negative correlations were present (*Society* and *Indirect Drivers*). *Exogenous Drivers* was the only component that showed no significant correlation.

With respect to the relationships among RAM components, there were both positive and negative relationships and both linear and nonlinear ones (Fig. 5; SM9). All proposed relations between RAM components were empirically supported, except for the *Ecosystem Services* → *Indirect Drivers* relationship which could not be established from the data. Also, the links between the Nature and Society components, and the *Ecosystem Services* component were weak as only one Natural basis indicator (*Average temperature*) and two Society indicators, one from *Social basis* (*Death rate*) and one from *Social condition* (*Living births*), could be established empirically.

Table 1 System of sustainability indicators for the Usumacinta River basin grouped by component of the analytical model (Fig. 1)

Indicator	Acronym	Sust. sign
Indirect drivers		
Competitiveness	CO	+
Environmental services payment	ESP	+
Gross domestic product allocated to education and health services	GDPS	+
Natural protected areas surface	NPA	+
Human activities		
Consumer price index	CPI	0
Daily oil production	OP	–
Farming surface	FAS	–
Firewood usage	FU	–
Reforested surface	RS	+
Urban population	UP	+
Direct drivers		
Burned surface	BS	–
Escherichia coli in rivers	EC	–
Fecal coliforms in rivers	FC	–
Forest loss	FL	–
Urban waste	UW	–
Exogenous drivers		
Crimes	CR	–
Disasters	DI	–
Female homicides	FH	–
Hydric stress	HS	–
Landslide risk	LR	–
Male homicides	MH	–
Migration	MI	–
Vulnerability to climate change	VCC	–
Natural condition		
Endangered birds	EB	+
Endangered mammals	EM	+
Endangered vertebrates	EV	+
Endangered species	ESpp	+
Forest surface	FS	+
Natural basis		
Accumulated precipitation	AP	0
Average temperature	AT	0
Social condition		
Average schooling	AS	+
Birth rate	BR	-
DTP vaccination	DTP	+
Illiteracy	IL	–
Infant mortality	IM	–
Living births	LB	+
Maternal mortality	MM	–
MMR vaccination	MMR	+
Occupied working-age population	WP	+
Poverty	PO	–

Scenarios of indirect drivers change and their impact on the socioenvironment

We explored scenarios of a 10% increase in the indicators associated with the *Indirect Drivers* component: *Competitiveness*, *Ecosystem Services payment*, *Gross domestic*

Table 1 (continued)

Indicator	Acronym	Sust. sign
Social basis		
Age 0–14	AG1	0
Age 15–64	AG2	0
Age 65+	AG3	0
Death rate	DR	0
Economic dependency	ECD	0
Indigenous population	IP	0
Ecosystem services		
Forest biomass	FB	+
Anthropogenic assets		
Drinking water	DW	+
Household access to electricity	EA	+
Internet users	IU	+
Paved roads	PR	0
Sewage system	SS	+
Telephone users	TU	+

Each indicator has an associated sustainability sign: +, an increase in the value of the indicator promotes sustainability; –, a decrease in the value of the indicator promotes sustainability; and 0, the value of the indicator has no impact on sustainability; 0, the indicator is not included in the index because its change is not associated with changes in sustainability

product allocated to education and health services and *Natural protected areas surface* (*Natural protected areas surface*) (Fig. 6).

An increase in *Competitiveness* produced, in general, changes in the socioenvironment that do not increase sustainability (Fig. 6a). This is because, although *Human Activities* and *Natural Condition* move toward sustainability, *Direct Drivers*, *Social condition* and *Ecosystem Services* counteract this trend. Under this scenario, the *Human Activities* index increases 1.14%, mainly due to a reduction in *Daily oil production* (10.86%) and *Farming surface* (4.34%). As a result, the *Direct Drivers* index decreases 0.44%, because *Fecal coliforms* increase 2.45%. This translated into a positive effect on *Natural Condition* (0.10%), mainly due to an increase in *Endangered vertebrates* (0.29%), and a negative effect on *Social condition* (−0.32%), due to an increase in *Infant mortality* (0.30%).

The best result in terms of sustainability was obtained when increasing *Ecosystem Services payment* by 10% (Fig. 6b). Such an increase translated into an increase in the sustainability of all components, with an increase of 0.18% in the *Ecosystem Services* component. The increase in *Human Activities*'s sustainability was mainly due to a decrease in *Oil production* (Daily oil production; 31.01%). The subsequent increase in *Direct Drivers* was mainly due to a decrease in *Escherichia coli* and *Fecal coliforms* (2.02 and 1.00%, respectively), and the increase in *Social condition* and *Natural condition* can be ascribed to the reduction

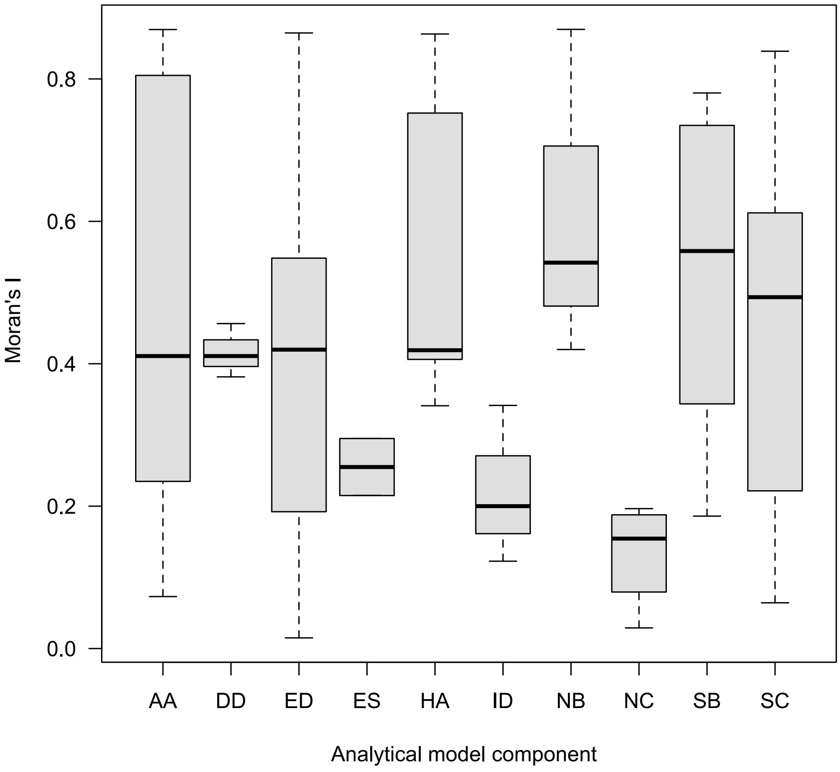
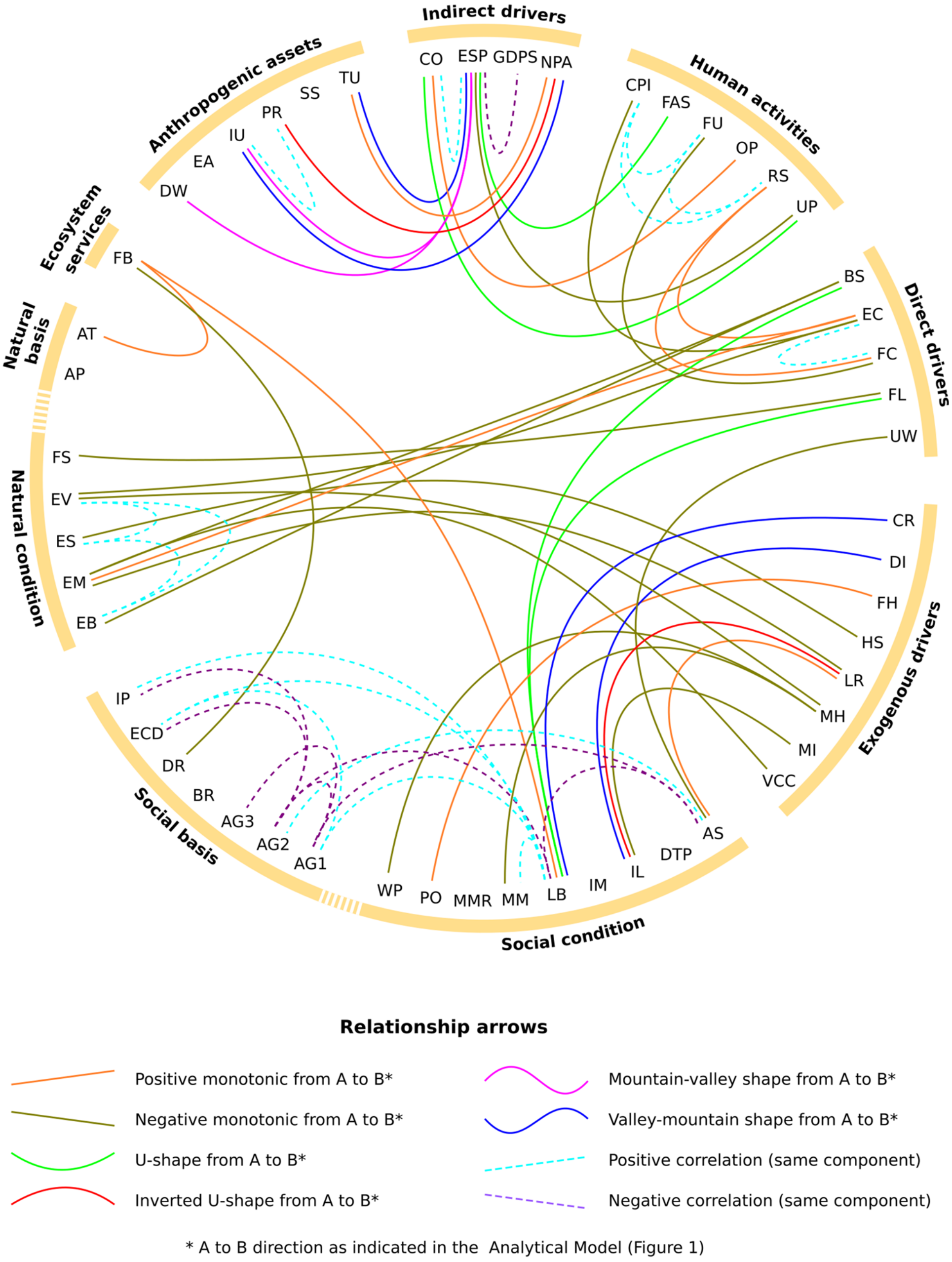


Fig. 4 Distribution of the Moran's *I* spatial autocorrelation index among the indicators grouped by analytical model component: *AA* anthropogenic assets; *DD* direct drivers; *ED* exogenous drivers; *ES* ecosystem services; *ID* indirect drivers; *HA* human activities; *NB* natural basis; *NC* natural condition; *SB* social basis; *SC* social condition

Fig. 5 Relations between indicators grouped by analytical model components. Indicator acronyms: see Table 1. Only significant relations are presented according to the likelihood ratio tests (SM9)



in *Illiteracy* (0.10%) and *Endangered vertebrates* (0.12%), respectively.

In turn, increasing 10% *Gross domestic product allocated to education and health services* had the worst effect on the sustainability of the *Human Activities* component (-2.79%) by increasing *Farming surface* (1.88%), *Urban population* (0.72%) and *Oil production* (0.71%) (Fig. 6c). This negative effect on Human Activities has, as a consequence, a reduction in the sustainability of both the *Social condition* and *Natural condition* components.

Finally, an increase of 10% in *Natural protected areas surface* is the most conservative outcome as it maintains relatively stable the current sustainability conditions of all components of the URB system (Fig. 6d).

Discussion

Challenges in the integration of data

The selected sustainability indicators displayed a wide range in the quality and quantity of their information, making it difficult to compare them between countries. This may be due to the different interests of each country, which determine

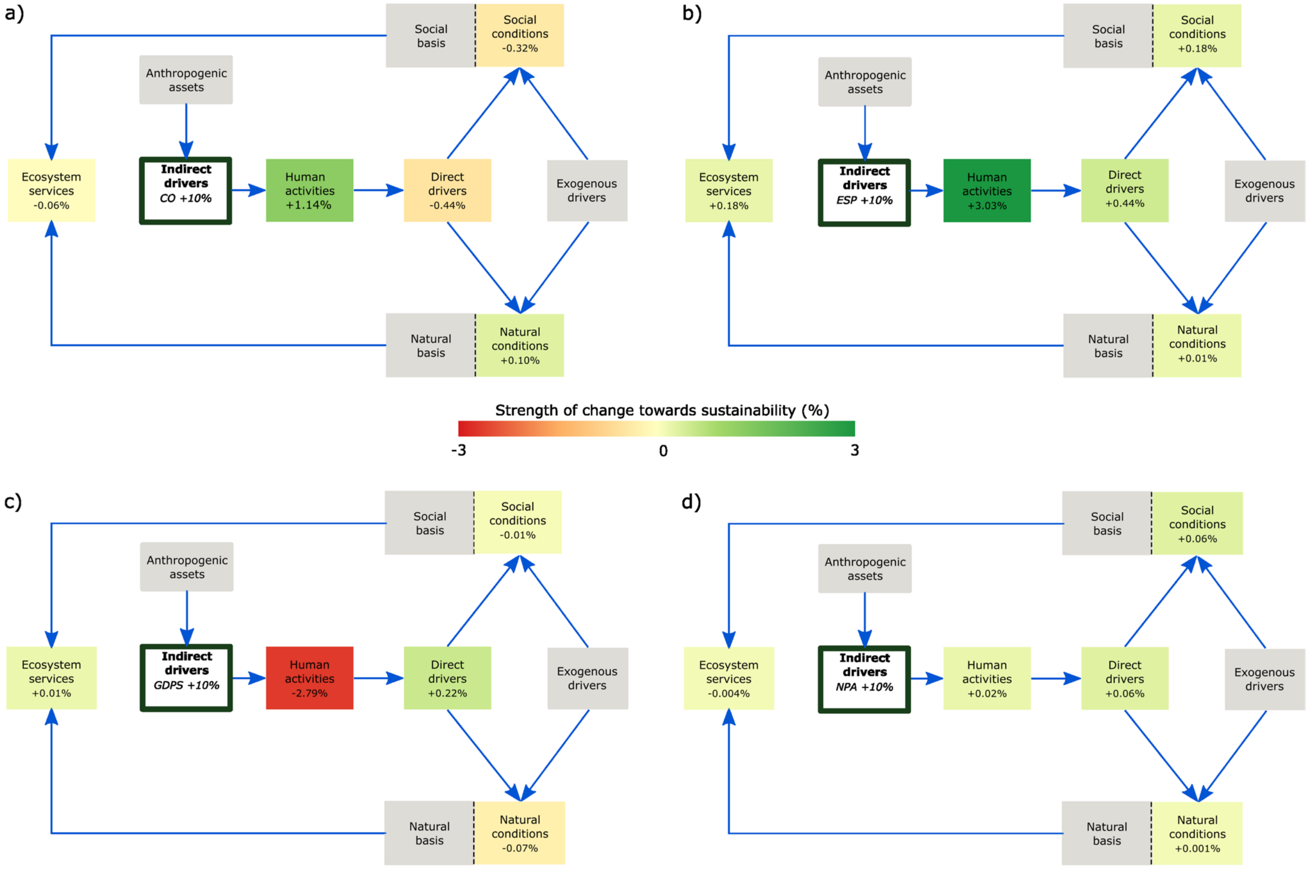


Fig. 6 Changes toward sustainability in the realized analytical model components indices after a 10% increase in **a** competitiveness (CO), **b** environmental services payment (ESP), **c** gross domestic product allocated to education and health services (GDPS) or **d** natural protected areas surface (NPA)

the type of information and research that is generated. In Guatemala, there is relatively limited scientific activity (Bonilla and Serafim 2021; Lemarchand 2017), since, compared with Mexico, where there are 244 full-time scientific researchers per million inhabitants, Guatemala only has 27 (Bolaños-Guerra and Tigau 2020; World Bank 2019).

In general, the indicators in both countries have a low temporal resolution. Environmental indicators (e.g., air, water, soil, waste and biodiversity) have quinquennial updates, although in some cases they were found at intervals of up to eight years. The difficulty of measuring environmental variables has to do with their nature and the high costs involved in monitoring them, the technological equipment and the human resources required to carry out the different activities (Anderson 2018; Fürst 2021; Stephenson and Stengel 2020; Stephenson et al. 2022); unlike population statistics which are politically more profitable than environmental ones. A particularly poignant case was the need to use indicators of the number of endangered species as a proxy of the extant species in a municipality: those with the largest numbers of endangered species are expected to also have the highest species richness, which also explains the positive sign in terms of sustainability we adjudicated them (Table 1).

Spatial analysis of the sustainability indicators

Urban planning and territorial management studies have identified spatial clusters of socioeconomic variables and sustainability indicators, where an absence of spatial patterns between social and Indirect Drivers variables was observed, which was interpreted as a lack of coordination of actions in the administrative hierarchy (Buzai 2014; Orenstein and Shach-Pinsley 2017; Shaker 2015). Such a scenario makes it difficult, inefficient and even unfeasible, to achieve sustainable development goals at the state, regional and national levels (Shaker 2015). Even a random pattern can become adverse if conditions of socioenvironmental vulnerability dominate the region. A case where a favorable condition overlapped with random patterns occurred for the Ecosystem Services component: *Forest biomass* represented a progress toward environmental sustainability in the Usumacinta River basin, but, given the unsustainable state of the *Forest loss*, *Reforested surface*, *Landslide risk* and

Environmental services payment indicators, it is relevant to continue promoting sustainable management of forest resources (Lior et al. 2018).

On the contrary, the Condition component stood out for contributing strongly to environmental sustainability since a good part of the Usumacinta River basin municipalities presented high values in its indicators. Indirect Drivers and Exogenous Drivers were the components that had a high impact on the state of sustainability of the region, so an improvement in these would lead to an improvement in the region. As for the Exogenous Drivers component, the indicators are difficult to control because they involve causes with a broader scale domain than that of the Usumacinta River basin.

Relations within components

When analyzing the correlations that were obtained within each component of the analytical model, along with the geospatial information of the indicators in the SIMULA platform, most of the correlations established were consistent with the literature available for the region.

Human Activities component: we observe that the largest proportion of *Reforested surface* is in Guatemala, mainly in the departments of Alta and Baja Verapaz, and to a lesser extent in the other departments (CCGS-IDEGeo 2019). Guatemala has a partially decentralized forest management in which local governments can charge fees for services they consider convenient and enforce their own rules as long as these do not contradict national laws (Fernández-Luiña et al. 2022; Priebe et al. 2015). This decentralization has increased the focus on reforestation in Guatemala (Paulson et al. 2015). In turn, the direct relationship between *Consumer price index* and *Firewood usage* can be explained by the lack of purchasing power of the inhabitants, who consume cheap energy sources, such as firewood (Mori and Yépez-García 2020). In rural Guatemala, 54% of households use wood for cooking (Portillo et al. 2021). In Mexico, the highest use of firewood was observed in Chiapas (CCGS-IDEGeo 2019), a fact confirmed by other studies that locate its consumption in rural communities (Ghilardi et al. 2007; Marquez-Reynoso et al. 2017).

Direct Drivers component: the direct correlation between *Escherichia coli* and *Fecal coliforms* was expected, as both indicators are measures of biological pollution in water bodies. The highest concentration of these elements was found in southeast Tabasco, northern Chiapas, and eastern Petén (CCGS-IDEGeo 2019). In Guatemala, 5% of collected wastewater is treated and the rest is returned to the water bodies, with the 87 wastewater treatment plants in the country only partially operational due to maintenance problems (Rodríguez et al. 2022; von Sperling 2016). In Mexico, Tabasco has 97% sewerage coverage, while Chiapas and Campeche have 82% and 85%, respectively (CONAGUA 2013).

Social component: the *Age 0–14* indicator negatively correlated with *Age 15–64* and *Age 65+* due to their complementariness; this also explains the negative and positive correlations of *Economic dependency* with *Age 15–64* and *Age 0–14*, respectively. This behavior may be due to the population dynamics of each country, since, although similar, Guatemala still has a growing population, while in Mexico the population is beginning to show a stationary profile (CCGS-IDEGeo 2019). In turn, *Age 15–64* was negatively correlated with *Indigenous population*, which means that those municipalities with larger indigenous populations have a relatively lower proportion of their populations in the 15–64 age bracket (INEGI 2022). *Living births* follow a similar pattern, with positive correlations with *Age 0–14*, *Economic dependency*, *Indigenous population* and *Maternal mortality* (Arriaza et al. 2022; Servan-Mori et al. 2016). Finally, *Average schooling* is negatively correlated with both *Living births* and *Age 0–14* and, due to complementarity, positively correlated with *Age 15–64*.

Natural component: as expected, all groups of endangered species were positively correlated.

Anthropogenic Assets component: the direct correlation between *Paved roads* and *Internet users* can potentially be attributed to: (1) the unequal geographical distribution of Internet users in both countries, since nearly 70% live in urban environments (García 2019; Melgar 2016), characterized by a high density of paved roads and by inhabitants with higher incomes; and (2) the predominance of Internet service providers for home users consisting of private entities that use wired networks whose layout requires physical access to the users' towns and homes.

Relations between components

The relations between the socioenvironmental components established by the analytical model were consistent with some of the social and environmental dynamics and patterns described for the region by several authors. We emphasize now some of the resulting relationships that we consider more relevant.

Indirect Drivers → Human Activities relation: The *Competitiveness* indicator showed a positive relationship with *Daily oil production* and *Urban population*, possibly due to the economic opportunities that the latter creates in the cities where it develops (Fry and Hilburn 2020; Pinkus-Rendón and Contreras-Sánchez 2012; Tudela 1989). *Environmental services payment* shows a nonlinear relationship with *Farming surface* because landowners may or may not apply for these payment programs, with those receiving the largest amounts having relatively larger areas (~20%) devoted to agricultural activities located in the upper part of the Usumacinta River basin (Tacconi 2012; Izquierdo-Tort 2018); and, as expected, *Environmental services payment* shows a negative relation with *Urban population*, as larger payments are assigned to areas with lower population densities.

Human Activities → Direct Drivers relation: *Escherichia coli in rivers* decreases as *Consumer price index* increases because high *Consumer price index* values correlate with better sewage water management (CONAGUA 2013). *Reforested surface* shows positive relationships with *Escherichia coli in rivers* and *Fecal coliforms in rivers*, because reforestation mainly takes place in rural areas.

Direct Drivers + Exogenous Drivers → Nature Condition relation: As expected, *Forest surface* was negatively influenced by *Forest loss*. The indicators associated with threat (i.e., *Endangered species, Endangered vertebrates*, *Endangered mammals* and *Endangered birds*) reflect the overall diversity in a region; this explains the relations found with these indicators. Thus, low *Hydric stress* corresponds to humid regions with high species diversity (Frank et al. 2014); regions with a high *Burned surface* have lower diversities of both birds and mammals (Kelly et al. 2020); regions with high diversity will be less vulnerable to climate change (*Vulnerability to climate change*; Trew and Maclean 2021) and correlate with lower risks of landslide (*Landslide risk*; Li et al. 2022).

Direct Drivers + Exogenous Drivers → Society Condition relation: Exogenous Drivers displayed more relations with Society Condition than Direct Drivers. Thus, violence, in the form of *Female homicides* and *Crimes*, was positively correlated with *Poverty*; poverty has been signaled as a main explanatory factor of the high homicide rates in Latin America, with Guatemala being one of the countries with the highest poverty and homicide rates (Hernández Bringas 2022; Rivera 2016). *Illiteracy* was also explained by Exogenous Drivers factors: negatively by *Migration* and natural *Disasters*. This is because migrants, with high illiteracy levels, settle or transit through regions in Mexico with relatively lower levels of illiteracy (Escamilla-Guerrero and Lopez-Alonso 2019); conversely, Tabasco, Mexico, which displays low illiteracy levels (Chiatchoua and Romero 2022), displays high vulnerability levels to hydrometeorological disasters (Ceragene et al. 2023; Gurri et al. 2019). *Average schooling* was associated positively with *Landslide risk* and negatively with *Urban waste* mainly because Mexico, although having higher schooling levels than Guatemala, has the highest landslide risks in the URB, with the most affected population inhabiting mountain slopes (INECC 2020); in turn, Guatemala displays higher urban waste volumes, as well as lower educational levels, particularly in its northern region (CIEN 2019), with respect to Mexico.

Nature Condition + Society Condition → Ecosystem Services relation: The *Forest biomass* indicator was related positively with *Temperature*; this is consistent with the fact that environmental temperature is a good predictor of vegetation biomass (Reich et al. 2014).

Scenarios of indirect drivers change and their impact on the socioenvironment

From the scenarios examined here, a single public policy translated into benefits in terms of sustainability for the entire socioenvironmental system. This was the policy designed with a particular component of the system in mind, the Ecosystem Services payment, which increased the Ecosystem Services component while reducing the Human Activities and its effects. The worst scenario, involving an increase in health and education governmental investment, which actually did not improve the sustainability of the Social component.

Sustainable development for developing countries represents a challenge in that social growth, i.e., an improvement in the living standard of people, including health and education, requires an investment in infrastructure projects that may entail adverse effects on the environment (Kumo et al. 2021). Thus, social development, although essential for sustainable development (Pickett et al. 2014; Shaker 2015), is not enough as a single strategy for socioenvironmental sustainability.

Our results associated with an increase in Natural protected areas surface are also very limited as an isolated governmental sustainability strategy. An increase of natural protected areas falls within the so-called land-sparing policies, which seeks to protect land from human intervention and use more intensely and in a sustainable way those areas already under human exploitation. Both Mexico and Guatemala have implemented these policies: Mexico has 215,000 km^2 (11%) of protected areas (CONANP 2022), while Guatemala has protected 22,000 km^2 (31%) of its territory (SIGAP 2019). A long-lasting debate exists between this strategy and the land-sharing strategy, which consists of protecting less land but using more wildlife-friendly techniques in those areas subject to human exploitation (Collier et al. 2018; Tello and González de Molina 2018), and our results support the idea that, rather than a debate, both policies are required and are complementary if socioenviromental sustainability is to be attained (Kremen 2015; Crespin and Simonetti 2019). This is in line with what other authors have proposed for the region (Crespin and García-Villalta 2014; de la Vega-Leinert et al. 2016; Boillat et al. 2017).

Ecosystem Services payment is a conservation policy first applied in Latin America, in which, by paying landowners conditioned on forest protection, deforestation and land use change is disincentivized (Bottazzi et al. 2018; Fiorini et al. 2020; Wunder 2015). In the URB region, Mexico's payment programs started in 2003 through the forestry section of the environmental secretary (DOF 2003; Izquierdo-Tort 2018; Osborne and Shapiro-Garza 2018), and in Guatemala such programs started a decade ago with the GuateCarbon initiative (CONAP 2017; Alejo et al. 2022; Gray 2020; Hodgdon et al. 2013), both falling within the REDD + UN's programme (UNFCCC-COP 2006; Sukhdev et al. 2021). Evidence of the social and ecological benefits of Ecosystem Services payment is scarce (Ingram et al. 2014; Brownson et al. 2020; Wunder et al. 2020), and this study demonstrates its benefits in relation with other public policies that have been considered beneficial to the overall sustainability of territories.

Considerations

It is important to emphasize that this study aims to evaluate, in a quantitative manner, the way in which public policies impact a socioenvironmental system in all its interconnected components. The study demonstrates how public, periodic and accessible information on the public policies implemented in a region along with information on the rest of the components of the system can provide evidence on the differentiated impact policies have on a region, and thus serve as a basis to improve existing policies if sustainable development is to be attained.

However, we recognize that in performing this study we are making several assumptions and that their violation would affect our results. First, we assume that the analytical model proposed by MZ and collaborators (CCGS 2019) is a correct description of how, at least in the short run, the studied socioenvironmental system functions. Because its definition is outside the scope of this manuscript, we do not discuss its adequacy in describing the system, but only emphasize that the model is simple and can be used for our objective, which was the simulation of alternative scenarios of system states: two considerations to be taken into account when developing a systems model (Kelly et al. 2013).

Second, assigning a sustainability sign to these indicators was challenging and can be controversial due to the opposing effects on different components they may have (Reid and Rout 2020). A clear example is the paved roads: while they represent an asset for the social and economic development of the population, they are the gateway to land use change and the exploitation of natural resources (Alamgir et al. 2017). These opposing effects must translate into different simulation outcomes if we are to consider the net effect of these processes as positive or negative.

Third, as stated above, comparable data between both countries represented a major challenge and the system of sustainability indicators shows a limited image of the URB socioenviromental system. This is particularly true for the Ecosystem Services component, for which we could only obtain information on an indicator, *Forest biomass*, as this is the most common ecosystem service studied (Balvanera et al. 2012; Acharya et al. 2019) and serves as a proxy for carbon storage, climate and water regulation, oxygen supply and habitat provision (Egoh et al. 2012; Taye et al. 2021). Therefore, we emphasize the need for more governamental efforts on the systematic quantification and monitoring of the services provided by the different ecosystems present in these two countries.

Conclusions

The study of territories from a socioenvironmental perspective is always a challenging endeavor given the complexity involved in describing these systems. As our study demonstrates, several steps had to be performed to properly describe the system associated with the Usumacinta River basin. Based on an analytical model structuring the dynamics of the system, a set of indicators associated with this structure and data on these indicators, we were able to identify the strength in the network of relations between components of the system and explore how changes in public policies would impact the entire Usumacinta River basin system. Our results allowed us to establish that environmental services payments improve the overall sustainability of the basin, and that a conservative strategy of environmental protection should be considered if socioenvironmental sustainability is to be attained. However, we must recognize that the limitation of information comparable between the two countries that constitute the region limits our conclusions and that more information is required to explore alternative causal pathways different from those proposed here. Nonetheless, our results demonstrate the benefits of having a socioenvironmental systems perspective to understand sustainability and propose informed interventions on large, complex and diverse territories.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11625-025-01641-7.

Acknowledgements The authors thank the researchers who helped with feedback on indicator selection, specially J. Alberto Gallardo-Cruz, Mauricio Cervantes, Federico Morales, Pilar Fuerte, Mónica Velasco, Margarita Parás, Edith Kauffer and Yosu Rodríguez. We thank the Center for Global Change and Sustainability, A.C., for providing us with all the necessary resources to carry out this research work, and the Research Center for Geospatial Information Sciences (CentroGeo) for hosting the SIMULA microsite in its IDEGeo platform.

Author contributions EJG, MZ and JC contributed to the study conception and design. Material preparation and data collection were performed by AA-A, CC and PEP-C. Data analysis was performed by FS and CC. The first draft of the manuscript was written by EJG, AA-A, CC and FS. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding The authors received funding from the FORDECYT-CONACYT project no. 273646. Consejo Nacional de Ciencia y Tecnología, 273646, Julia Carabias.

Data availability No original data were generated for this study. The sources of the data used are described in SM7.

Declarations

Conflict of interests The authors have no relevant financial or non-financial interests to disclose.

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