Environmental & Socio-economic Studies

DOI: 10.2478/environ-2026-0002

Environ. Socio.-econ. Stud., **2026, 14, 1: 18-35**

Original article

Status of socio-ecological systems in central-eastern Mexico: Identifying priority sites to improve resilience in a biocultural territory

Omar Larios-Lozano[1], Jessica Bravo-Cadena[1,2], Numa P. Pavón[1]*, María Teresa Pulido-Silva[1], Arturo Sánchez-González[1]

[1]Centro de Investigaciones Biológicas, Universidad Autónoma del Estado de Hidalgo. Carretera Pachuca-Tulancingo km 4.5, C.P. 42184, Mineral de la Reforma, Hidalgo, México
[2]Instituto Tecnológico Superior del Oriente del Estado de Hidalgo. Tecnológico Nacional del México. Carretera Apan-Tepeapulco Km 3.5, Colonia Las Peñitas, C.P. 43900, Apan Hidalgo, México
E–mail address (corresponding author): npavon@uaeh.edu.mx
ORCID iD: Omar Larios-Lozano: https://orcid.org/0000-0003-2595-9421; Jessica Bravo-Cadena: https://orcid.org/0000-0001-8032-9938; Numa P. Pavón: https://orcid.org/0000-0003-0666-5268; María Teresa Pulido-Silva: https://orcid.org/0000-0003-1307-9574; Arturo Sánchez-González: https://orcid.org/ 0000-0002-3190-8789

ABSTRACT

Social-ecological systems (SES) are understood as human–environment systems that encompass all ecological and technological structures relevant to, and shaped by, human actions. They are complex systems in nature, comprising two main components – social and ecological – along with their numerous subcomponents. For analytical purposes, the SES concept must be both operational and measurable, which requires defining spatial and temporal boundaries. In this study, the municipality was selected as the basic territorial and administrative unit. In spite of their importance, evaluations and mapping of SES remain scarce, particularly in Latin America. This study assessed the SES status in a region of central-eastern Mexico - a priority biocultural region for conservation and development. The aim was to identify critical areas for interventions to enhance socio-ecological resilience and understand the key factors influencing SES. Results indicated a generally low SES status per municipality, with values ranging from -0.244 to 0.361. The highest values were observed in municipalities with high ecological integrity, low sensitivity to biophysical hazards, and stable ecosystem service availability. Spatial correlation analysis revealed a cold spot in the south-eastern area, where municipalities exhibited the lowest resilience and SES status. In contrast, a hotspot with the highest values was found in the centre of the study area, where the infrastructure (i.e., roads, hospitals) was first developed because of silver mining. A generalized linear model showed a negative correlation between Indigenous people and SES status. Urgent actions are needed to improve communication, healthcare, education, economic opportunities, to reduce their vulnerability to environmental challenges.

KEY WORDS: environmental vulnerability, governance, Sierra Madre Oriental, socio-ecological index, spatial analysis

ARTICLE HISTORY: received 20 May 2025; received in revised form 21 December 2025; accepted 7 January 2026

1. Introduction

Socio-ecological systems (SES), characterized by complex interactions between social and ecological components (Folke, 2006; Thonicke et al., 2020), can be a tool for generating proposals aimed at transforming these systems toward more sustainable, fair, and equitable futures (Bigg et al., 2022). Resilience and exposure to environmental challenges are essential parameters in SES analysis. Resilience refers to a system's capacity to maintain its functions despite external or internal pressures (Folke, 2006; Thonicke et al., 2020). Stressors impacting SES can include extreme climatic events (e.g., heat waves, droughts, and floods) and social phenomena (e.g., public shifts, change of government, religious conflicts, economic crises, and migration). Enhancing the resilience of coupled SES across spatial, temporal, and institutional scales is therefore critical (Thonicke et al., 2020).

Communities exhibit greater resilience when social, economic, cultural, and political factors are well developed and they become more vulnerable when one or more of these factors are weak or underdeveloped (Wilson et al., 2018). Governance plays a fundamental role in socio-ecological resilience by ensuring organizational capacity and proactive measures to maintain SES health and address socio-environmental challenges like climate change. The participation of local communities in decision-making processes is vital for decentralized governance (Turner et al., 2022), where traditional knowledge holds significant value.

SES frameworks have been utilized for environmental diagnosis and for developing mitigation and adaptation strategies to address both natural and anthropogenic environmental problems (Estoque & Murayama, 2017; Gonzalez-Redin et al., 2019). For instance, the SES has been applied in natural areas rehabilitation, local governance (Cervantes et al., 2014), evaluating the impacts of tourism, oil, and fishing activities on resilience (Ávila & Espejel, 2020), identifying disturbance sources for rehabilitation mechanisms (De la Torre-Valdez & Moreno-Vázquez, 2019), and analysing drivers´ impacts on hydrological ecosystem services (Merlo-Galeazzi et al., 2024). Several methodological approaches have been developed for studying SES. One is the use of index-based analytical frameworks, which combine multiple indicators to evaluate both the social and natural components of SES, thereby assessing their current state or condition (Estoque & Murayama, 2014). To assess the state of an SES, it is essential to have data that enable the analysis of its social and ecological subcomponents, as well as their interactions. For this purpose, the information must be constrained to the SES's area of influence. In this regard, a geopolitical approach has been adopted to define boundaries, using the country, state, and municipality as the basic units (Estoque & Murayama, 2014, 2017). Another approach is system dynamics, which can model the causal relationships between different components of SES and predict their future behaviour. In addition, participatory methods have been incorporated into assessments, engaging social groups to integrate stakeholder perspectives. This not only broadens understanding but also improves management strategies for SES (Proswitz et al., 2021). Spatially explicit assessments are crucial in formulating environmental policy and guiding decision-making processes since maps help identify the most vulnerable and high-priority areas for intervention. These efforts can enhance SES conditions and, consequently, human well-being (Battamo et al., 2021; Bollettino et al., 2017), however, such studies remain scarce (Martín-López et al., 2017; Yang et al., 2020).

In Mexico a significant spatial overlap exists between areas of high biological and cultural diversity, prompting the designation of "priority biocultural regions for conservation and development" (Boege, 2008). The stewardship of these priority biocultural regions is critical; their governance presents substantial challenges, requiring transdisciplinary approaches and multi-scalar geographic analysis – encompassing local, municipal, state, and national levels. A priority biocultural region is located in the central-southern area of the Sierra Madre Oriental. This area was studied in depth through an institutional collaboration between Mexico's National Commission of Natural Protected Areas and the German International Cooperation Agency (GIZ), with the aim of formulating and proposing a new protected area known as the Sierra Madre Oriental Ecological Corridor (CESMO). As a result, numerous studies were conducted in the region, particularly on climate change (CONANP-GIZ, 2013), although CESMO was never officially established. In the light of this gap in a region of significant biocultural importance, this article provides a macro-scale overview intended to inform decision-makers at the municipal and state levels. Despite being a priority conservation biology area, the region suffers from high marginalization and severe environmental problems stemming from land-use changes, such as the conversion of forestry into agriculture and livestock areas (Leija-Loredo et al., 2018). Additional social challenges, including poor resource management, population growth, inadequate urban planning, and unsustainable economic models, further impact SES conditions (CONANP-GIZ, 2013).

From an operational perspective, SES provide a valuable framework for assessing quality of life based on the interaction between nature and society; however, studies of this kind remain scarce. Despite its ecological and cultural importance, the central-southern region of the Sierra Madre Oriental lacks a comprehensive diagnosis of the state of its SES. This region requires the implementation of strategies aimed at improving the quality of life of its inhabitants. Accordingly, such a diagnosis will serve as a tool for generating public policies and establishing programs that strengthen socio-ecological resilience in the face of environmental challenges, while promoting a nature-based quality of life. The objective of this study was to evaluate SES by considering both resilience and socio-ecological stressors, with the aim of identifying variables whose improvement could enhance resilience and the overall state of the SES. In addition, spatial analysis was applied to identify priority areas for intervention, where social and environmental conditions are so degraded that the quality of life is severely compromised.

1.1. Conceptual literature review

Different frameworks have been proposed to define Social-Ecological Systems (SES) and to facilitate their study, emphasizing the equal importance of their two primary components: the social and the natural. SES has been described as human–environment systems, encompassing all ecological and technological structures that are relevant to, and influenced by, human actions (Scholz & Binder, 2004). Similarly, SES have also been referred to as ecological–human systems, divided in two broad domains: humans and ecosystems (Raskin, 2008). Although a universal definition of SES remains elusive, these systems are generally understood as complex structures composed of two main components, social and ecological, and their multiple subcomponents. The social dimension includes various forms of human organization, such as political, economic, and social institutions, as well as ethical values, knowledge, ideology, and cultural identity. In contrast, the ecological dimension involves ecosystems, soil components, and a range of biological, climatic, hydrological, and physicochemical processes (Estoque & Murayama, 2014*).*

The inherent complexity of SES requires that their study be spatially and temporally bounded according to specific objectives and scopes. Socio-ecological systems can be conceived as nested structures; in other words, one SES may encompass others. This notion is similar to ecosystems, where a forest represents a single system but contains smaller ecosystems within it. For example, after rainfall in a forest, a pond may form, hosting various biotic and abiotic components, along with the flows of matter and energy necessary to qualify as an ecosystem. Each system functions autonomously, yet remains interconnected with others and provides reciprocal feedback.

Interactions among components and sub-components are what make SES complex and dynamic (Berkes & Folke, 1998). These interactions generate emergent properties that drive processes such as transformation, self-organization, and adaptation. The functioning of SES is influenced by dynamics that are not necessarily linear; they may include feedback loops or circular interactions, and unexpected events can push the system toward unpredictable trajectories (Raskin, 2008). Moreover, these interactions play a decisive role in shaping the resilience of SES, defined as their ability to maintain functionality despite socio-environmental pressures (Folke, 2006).

Socio-ecological resilience (SER) is a fundamental concept in SES that has also been applied across multiple disciplines. In ecology, it describes the processes that preserve the structural and functional integrity of systems (Holling, 1973). Within socio-ecological contexts, the resilience framework has been widely used in disaster assessment, watershed management, and adaptive cycle analysis (Walker et al., 2004). From a socio-ecological perspective, conceptual reviews emphasize a paradigm shift from stable states to complex adaptive states, in which systems can adjust to disturbances and identify appropriate policy responses for regional management (Li et al., 2020).

Furthermore, a distinction has been made between urban and regional analyses to explain how territorial systems can resist, absorb, adapt, and, when necessary, transform in response to disturbances (Cretney, 2014). At the regional scale, the concept of "regional economic resilience" has been introduced to move beyond static views of development and to examine economic trajectories subject to recurrent shocks, such as recessions or technological crises. This concept assumes that territories are capable of developing new growth trajectories after a disturbance. These trajectories not only allow them to recover but also enable them to transition into new developmental states (Simmie & Martin, 2010).

The existence of a link between resilience and competitiveness has been considered, relating the characteristics of a territory with economic success, social inclusion, and environmental sustainability, relating the characteristics of a territory to economic success, social inclusion, and environmental sustainability (Bristow, 2010). This perspective advocates for place-sensitive policies designed to strengthen adaptive capacities. Accordingly, regional resilience envisions new pathways for structural growth through the interaction of diverse sectors (Boschma, 2015). The analytical framework of this approach should identify the attributes and categories of regional responses to cycles of crisis and recovery, including resistance, recovery, and reorientation. This underscores that resilience is a multifaceted concept (Eraydin, 2016).

Various dimensions, properties, and scales of resilience have been identified – from community and urban levels to regional and national ones – highlighting that resilience functions both as a property and as a process. In the urban context, resilience refers to the capacity of urban systems – comprising institutions, infrastructure, and communities – to adapt to and recover from shocks and stressors, while maintaining essential functions and safeguarding long-term objectives (Chu et al., 2021; Brad & Dávila, 2022). Key aspects include: i) multidimensionality, encompassing the economy, institutions, networks, infrastructure, and community (Masik, 2022); ii) dynamics, expressed through cycles of resistance, recovery, adaptation, and transformation, as well as through social and institutional learning; iii) place-sensitivity, which depends on sectoral specialization and local institutional arrangements; and iv) long-term perspectives, which foster diversification and reconfiguration, enabling new developmental trajectories (Simmie & Martin, 2010).

The concept of resilience has shifted from merely restoring a system to its previous state after a disturbance to being understood as a dynamic and evolving process. This perspective emphasizes the reconfiguration of economic and social trajectories following natural or social disturbances. It enables planners to align territorial instruments – such as land use, infrastructure, mobility, and ecosystem services – with local capacities, including social capital, productive networks, and institutions, thereby supporting long-term rural well-being (Elekes et al., 2024). In rural areas, community participation and solidarity networks among localities are increasingly recognized as key drivers of recovery from socio-environmental pressures. Consequently, citizen engagement is as important as economic factors (Sowada, 2024). Decision-makers must also shift from a focus on stability toward an approach centred on evolutionary resilience, implementing inclusive policies that preserve essential functions while addressing territorial inequalities.

In several Latin American countries, significant differences persist between urban and rural systems. Strengthening resilience in rural areas requires investments in basic services to reduce vulnerability (Chu et al., 2021; Brad & Dávila, 2022). Furthermore, urban-rural interactions play a crucial role in enhancing rural resilience by improving access to markets, specialized services, knowledge, innovation, and labour flows. These interactions can facilitate the sustainable transformation of rural territories and improve quality of life by bringing essential services and opportunities closer to local communities. To achieve this, planning must be coordinated across multiple scales – local, municipal, and regional – while ensuring effective communication (Raskin, 2008; Woodruff et al., 2021; Shamsuddin, 2020).

In areas with Indigenous communities, peasant economies, and extractive industries intersect – resilience must prioritize the protection of rights, recognize the unique characteristics of each territory, and avoid one-size-fits-all solutions (Shamsuddin, 2020). The challenges in these regions are substantial, requiring a combination of productive diversification, resilient social infrastructure, collaborative governance, and adaptive social protection, all while ensuring equity and territorial justice. In this context, resilience has emerged as an operational framework that facilitates territorial planning, aiming to reduce vulnerabilities, strengthen local capacities, and sustainably enhance the well-being of rural households (Boschma, 2015). Recently, there has been a notable increase in publications on resilience, many of which emphasize the importance of a socio-ecological approach to socioeconomic development, natural resource management, and the mitigation of environmental pressures (Estoque & Murayama, 2017; Noble et al., 2021; Gonzales-Redin et al., 2019; Li et al., 2020).

Recent studies have applied the socio-ecological resilience framework to develop new theoretical models relevant to diverse contexts (McCool & Mandic, 2025). For example, a novel "Resilient Livelihood Framework" has been proposed, emphasizing the enhancement of human resilience through sustainable livelihoods, community resilience, and ecosystem services (Stotten et al., 2021). In the health domain, particularly regarding emerging health and environmental risks, researchers have advocated for linking human health to ecosystem management. This connection is grounded in the resilience of socio-ecological systems and the adaptive capacity of their participants, giving rise to the concept of a

"Socio-Ecological Health System" (De Garine-Wichatitsky et al., 2012).

On the other hand, the concept of multi-scale resilience has been introduced within the socio-ecological resilience framework. This approach investigates the factors that foster resilience among young people in rural areas facing risks to psychosocial development, taking into account the complex interactions among individual, social, and ecological elements (Ungar & Koubova, 2024; Khan et al., 2025). Similarly, the socio-ecological resilience perspective has been applied to study the extraction of ecosystem resources, particularly those associated with cultural heritage and traditional ecological knowledge. This approach highlights the factors influencing human behaviour, decision-making, activities, and overall well-being (Souther, 2025).

2. Materials and methods

The information for this work was obtained from databases available to the Mexican government at the municipal level, which allows for more rapid assessments of the status of complex systems such as socio-ecological systems. Table 1 shows the institutional sources from which the data used in this study were obtained.

2.1. Study area

The study area is located within a priority biocultural region for conservation and development (Boege, 2008), located in the central-southern part of the Sierra Madre Oriental, with 7,879.9 km^2 and an elevation gradient of 100 to 3000 m (Fig. 1). Due to its size and orography, the area is very heterogeneous, with varied climates, including semi-warm and temperate humid, with summer rains. The land use is mainly agricultural, but various mountain vegetation types are still preserved, such as tropical mountain cloud forest, coniferous forests, and oak forest (Suárez-Mota et al., 2017).

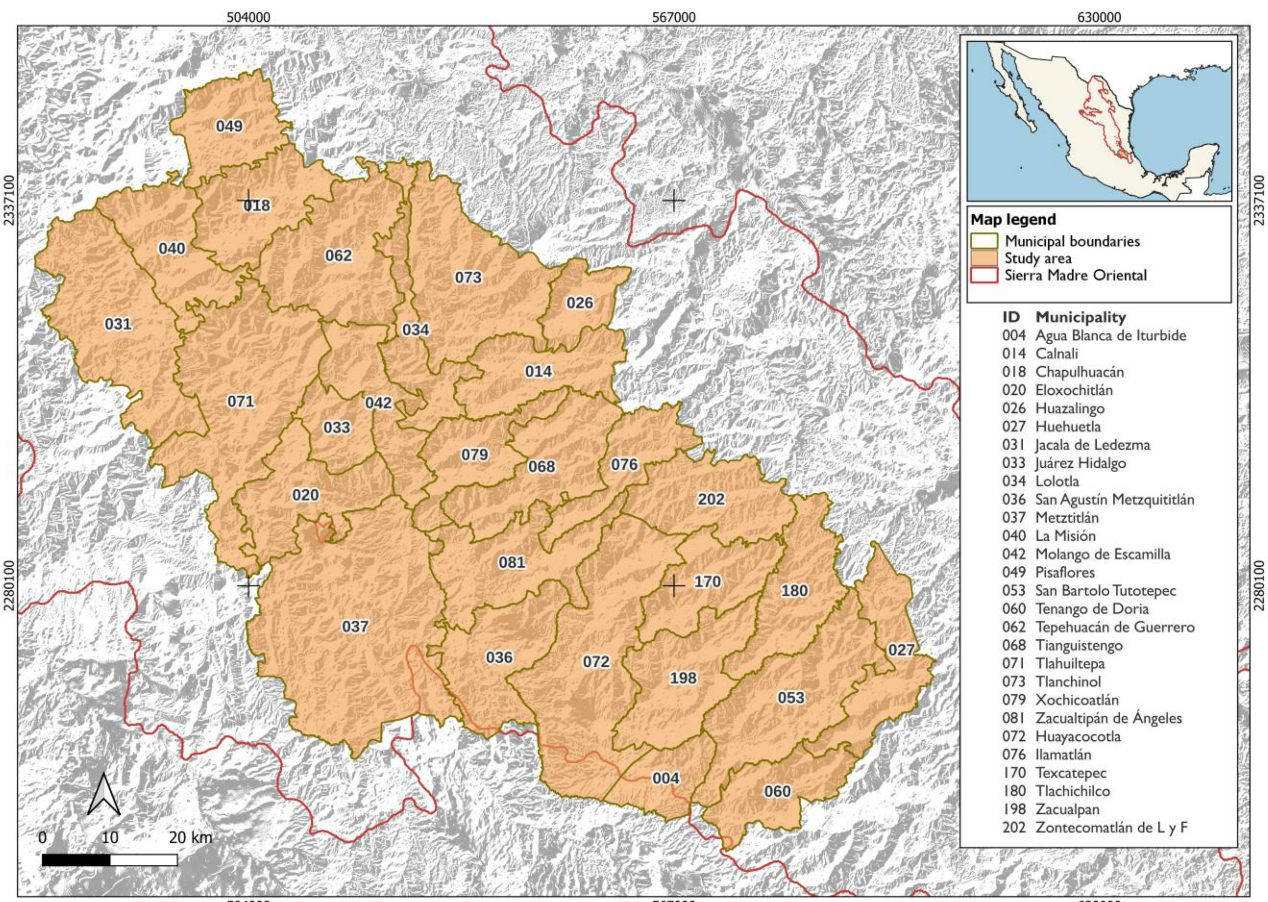

Fig. 1. Study area in the central-eastern part of Sierra Madre Oriental, Mexico. The geopolitical limits of the twenty-eight municipalities that comprise the study area are shown; the names of the municipalities were included

Table 1. Indicators and variables used to calculate Socio-Ecological Resilience (SER), Socio-Ecological Pressures (SEP), and the Socio-Ecological System Index (SESI). The data sources are different institutions of the Mexican government (*variables used to build the generalized linear model)

SESI components	Sub-components	Indicators	Explanation of what each index comprises	Data source
Socio-ecological resilience	Social integrity	Human development Index*	It evaluates human development base on its capacity to implement public policies through programs and projects. The calculation uses data on education, income, and health, and it enables comparisons across different levels of government.	Human Development Report (UNDP 2022)
		Poverty incidence rate*	It evaluates poverty in the population as the presence of some form of social or incomes deprivation. Poverty is a condition shaped by multiple dimensions such as ethnicity, age, disability, and gender, among others.	Municipal Poverty Report (CONEVAL 2020)
	Governance	Total financial resources generated		Expenditure Budget of the State of Hidalgo, Mexico for the 2020 fiscal year (Diario Official del Estado de Hidalgo 2022)
				Expenditure Budget of the State of Veracruz, 2020 (Gazeta Official del estado de Veracruz 2019)
		Total revenue collected (tax and non-tax revenue)*		Municipal Public Statistics and Finance (INEGI 2020a)
		Expenses on Social Services*		Federalized Spending (Destination of Spending) 2020. (Transparencia presupuestaria 2020)
		Economically active population rate*		Census of Population and Housing (INEGI 2020b)
		Income type*		Municipal Poverty Report (CONEVAL 2020)
		Crime solving effectiveness rate		Criminal Incidence of the Common Jurisdiction new methodology 2015-2021 (SSP 2021)
		Voter participation rate		Results of the 2019-2020 local electoral process (IEE 2020)
				Electoral process of the state of Veracruz, Municipal computing systems 2020-2021 (OPLE 2021)
		Indegenous population*		Census of Population and Housing (INEGI 2020b)
		Number of NGOs*		Directories of Civil Society Organizations. (SIRFOSC 2021)
		Council session number*		National Census of Municipal Governments and Territorial Demarcations (INEGI 2019)
		Number of initiatives approved by the councils*		
		Number of economic units*		
		Number of agrarian communities		Agricultural Census Framework (INEGI 2016)
		Number of farmers*		Agricola Census (INEGI 2007)
		Number of students per elementary school teacher*		Main numbers of the National Educational System 2020-2021(SEP 2021)
		Number of students per high school teacher		
		Number of students per bachelor teacher		
		Number of elemental schools		
		Number of public high schools*		

		Number of public bachelor schools*		
		Population over 15 years old with basic schooling		Census of Population and Housing (INEGI 2020)
		Total healthcare personnel per 1000 inhabitants*		Health Disaster Risk Atlas 2015 (SSH 2015)
		Number of health centers per 1000 inhabitants*		Unique Code for Health Establishments (SSH 2021)
		Homes with access to drinking water*		Census of Population and Housing (INEGI 2020)
		Number of people collecting waste*		National Census of Municipal Governments and Territorial Demarcations (INEGI 2019)
		Waste collected per day		
		Population with access to waste collection*		
	Ecological integrity	Environmental Services Value Index*	It was used to analyze the resources received by the municipality for the conservation of natural ecosystems and serves as an indicator of the environmental impact of the population. The value of the environmental services was estimated based on Mexico´s Payment for Ecosystem Services program.	Support Program for Sustainable Forest Development 2021 (CONAFOR 2021)
		Relationship between inhabitants and environmental services*	It evaluates the benefit of ecosystem services from a monetary perspective per inhabitant and per municipality. It was calculated by dividing the payment for ecosystem services by the number of inhabitants in each municipality.	Payment for Environmental Services (CONAFOR 2021). Census of Population and Housing (INEGI 2020b)
		Forest coverage index	It evaluates the conservation status of natural ecosystems in the municipalities. It measures the percentage of current forest cover per municipality. This was obtained by dividing the area with forest cover by the total area of the municipality. To calculate the area with forest cover, a spatial analysis was conducted using QGIS v. 3 and the country´s vector data on land use and vegetation, series VII.	Map of Land Use and Vegetation series III and VII (INEGI 2021)
Socio-ecological pressures	Biophysical hazard exposure	Landslide index*	It evaluates vulnerability to natural hazards within the municipality. It was estimated as the number of landslides occurring per municipality over the past year divided by the number of days in the period. Their incidence per municipality was projected spatially using QGIS v. 3. Vector resources available from the National Center for Disaster Prevention of Mexico. For landslides, data from Mexico´s Climate Change Vulnerability Atlas were used.	National Atlas of Vulnerability to Climate Change (INECC 2019). Vector data 1:250000
		Flood index*	It evaluates vulnerability to natural hazards within the municipality. It was estimated as the number of floods occurring per municipality over the past year divided by the number of days in the period. Their incidence per municipality was projected spatially using QGIS v. 3. Vector resources available from the National Center for Disaster Prevention of Mexico. For landslides, data from Mexico´s Climate Change Vulnerability Atlas were used.	National Risk Information System (Flood Danger Level Map at Municipal Level) (CENAPRED 2015). Vector data 1:250000
		Drought index*	It evaluates vulnerability to natural hazards within the municipality. It was estimated as the number of droughts occurring per municipality over the past year divided by the number of days in the period. Their incidence per municipality was projected spatially using QGIS v. 3. Vector resources available from the National Center for Disaster Prevention of Mexico. For landslides, data from Mexico´s Climate Change Vulnerability Atlas were used.	National Risk Information System (Drought Danger Level Map) (CENAPRED 2015). Vector data 1:250000
		Cyclone index*	It evaluates vulnerability to natural hazards within the municipality. It was estimated as the number of cyclones occurring per municipality over the past year divided by the number of days in the period. Their incidence per municipality was projected spatially using QGIS v. 3. Vector resources available from the National Center for Disaster Prevention of Mexico. For landslides, data from Mexico´s Climate	National Risk Information System (Danger Degree Map for Tropical Cyclones) (CENAPRED 2015). Vector data 1:250000

			Change Vulnerability Atlas were used.	
	Sensitivity to biophysical hazards	Population Density Index*	It evaluates land use in the municipality by the population. It was calculated by dividing the number of inhabitants of the municipality by its total area.	Census of Population and Housing (INEGI 2020b)
		Index of Protected Natural Areas*	It evaluates the potential for ecosystem-based adaptation focused on the conservation of natural ecosystems. It was calculated as the percentage of the municipality´s territory covered by protected natural areas. The percentage of protected area per municipality was calculated using QGIS v. 3, employing vector data of protected natural areas decreed within the municipality territory.	Federal Protected Natural Areas of Mexico (CONABIO 2021). State, Municipal, Ejidal, Community and Private Protected Natural Areas of Mexico (CONABIO 2020). Vector data 1:250000
	Socio-environmental pressures	Rate of change in Environmental Services*	It evaluates environmental degradation within municipalities through the spatiotemporal changes in the transformation and loss of original vegetation cover caused by human activities. Data on forest cover loss per municipality were obtained from Bravo-Cadena (unpublished data), who based the analysis on the Global Forest Watch program	Global Analysis & Discovery (Global Forest Change 2022). Vector data 1:250000

The study area, encompassing 28 municipalities, 22 in the state of Hidalgo and six in the state of Veracruz, Mexico. The area is a melting pot of indigenous cultures (Nahuas, Totonacos, Tepehuas, and Otomís de la Sierra) (Dow, 2005). The majority of the land is cooperatively owned, while a smaller percentage is privately owned. The total population of 433,845 inhabitants is a rich tapestry, with 24% being indigenous, primarily Nahuas (INEGI, 2020), distributed in a large number of localities (Fig 2). However, the area also faces significant challenges, with marginalization ranging from medium to very high and poverty exceeding 50% (INEGI, 2020). The area is also a hub of activity, with some 80 non-governmental organizations operating in the region.

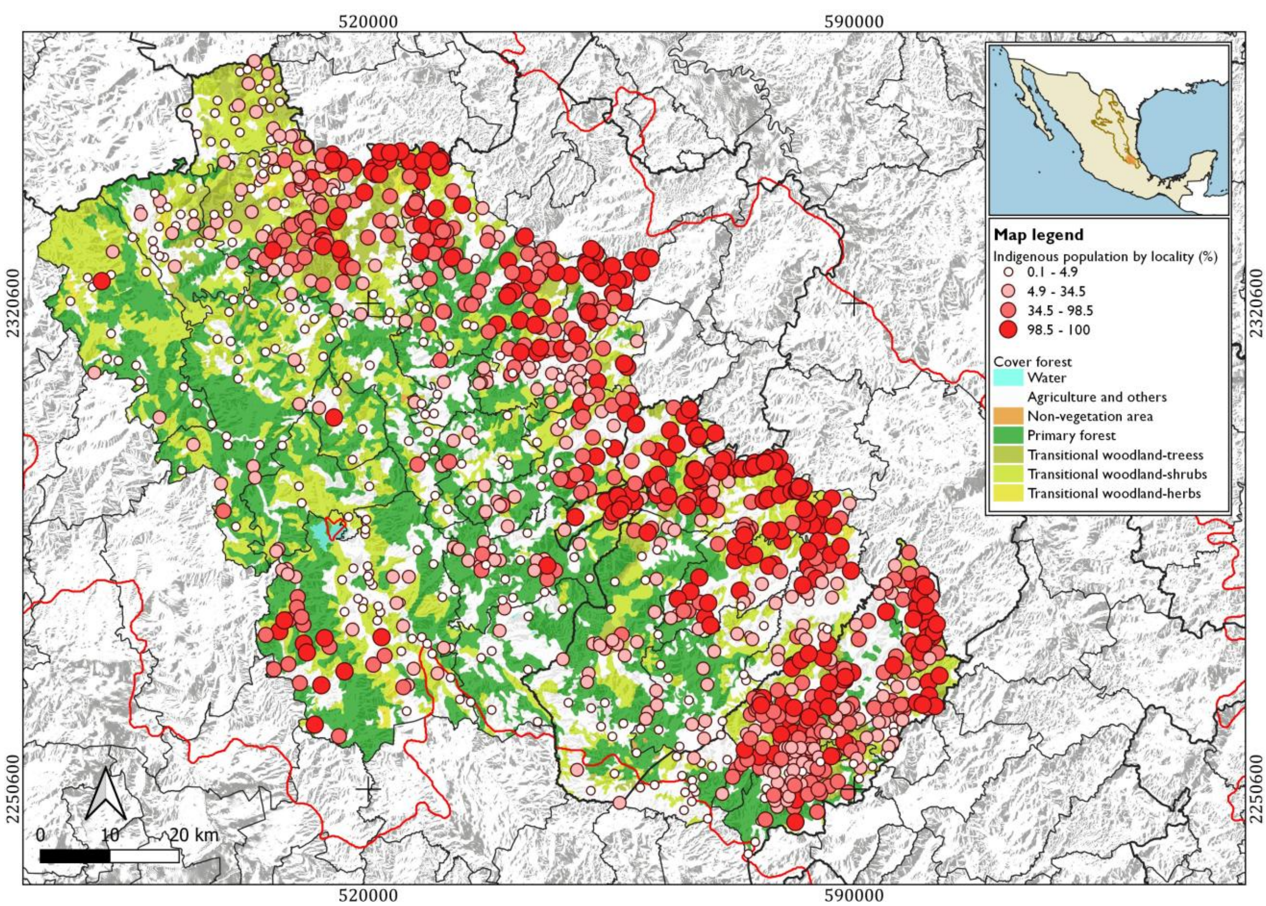

Fig. 2. Indigenous population by locality and land use in the central-eastern area of the Sierra Madre Oriental, Mexico. The size of de circles represents the percentage of indigenous inhabitant in each locality

The municipal scale was used to delimit the SES within the study area. This choice is justified by the lack of data at finer spatial scales, such as the locality. Social subcomponent data are available only at the municipal level, which represents the minimum unit of governance and the scale at which environmental policies are established (Kumar et al., 2021). Given the multiscale nature of SES, municipalities are considered the basic unit in an operational context and are essential to understanding socio-ecological interrelations at the local level (Ostrom, 2009). Other studies have assessed SES at even broader geopolitical scales, such as the national level (Estoque & Murayama, 2014, 2017).

2.2. State of the socio-ecological systems

The status of SES was estimated using the socio-ecological status index (SESI) (Estoque & Murayama, 2014). The SESI ranges from −1 (least desirable state) to 1 (desirable state). It is derived from the difference between socio-ecological resilience (SER) and socio-ecological pressures (SEP). Both the SER and SEP consist of three sub-components each, and in turn, each subcomponent is made up of one or more indicators (Table 1). The SER was defined as the system's overall integrity in coping with human–natural pressures while maintaining, organizing, and exercising its functions. Their subcomponents were: social integrity, ecological integrity, and governance (Table 1). The SEP was defined as the combined forces of stress factors and disturbances, both natural and anthropogenic. Their subcomponents were: bio-physical hazards exposure, sensitivity to biophysical hazards, and socio-environmental pressures (Table 1).

The analyses were carried out at the municipal level, for which a database was created with 39 variables, whose data was obtained from different government sources, of which 32 were used to calculate SER and seven for SEP (Table 1). Subsequently, the variables were standardized to values between 0 and 1 using the next equation.

$$\text{Standardized data} = (xi - \mu)/\sigma$$

Where: xi = data, μ =data average, and σ = standard deviation.

To determine if the average SESI differed from 0, a Student´s t-test was used. Differences between SER and SEP components were evaluated using Kruskal-Wallis tests.

2.3. Socio-ecological resilience

The SER was the average of their subcomponent values (social integrity, governance, and ecological integrity). SER values fluctuate between 0 (no resilience) and 1 (maximum resilience). The social integrity index was the average of the values of human development and poverty, obtained from 2010–2015 data (Table 1). The Good Governance Index was used as the governance component. It was defined by Virola et al. (2016) as strengthening institutions to address social problems, considering efficiency, transparency, accountability, civil society participation, and the rule of law. So, governance was the average calculated considering 27 variables that included aspects of efficiency, transparency, accountability, civil society participation and rule of law, among others (Table 1).

Ecological integrity was estimated as the average between the indices of ecosystem services, ecosystem services payment per inhabitant of the municipality, and forest cover. For ecological integrity, data on payment for ecosystem services by the Mexican government was used. A spatial analysis was conducted using QGIS V.3.16.11 (2020) software and vegetation vector data to calculate forest cover.

2.4. Socio-ecological pressures

The SEP was calculated as the average of the values of their sub-components (biophysical hazard exposure, sensitivity to biophysical hazards, and socio-environmental pressures) (Table 1). SEP values fluctuate between 0 (no pressure) and 1 (maximum pressure). Biophysical hazard exposure was the average of four indices (Table 1). Data were spatially projected using the natural breaks (Jenks) function in the QGIS program interface that maximizes class differences. The results are categorized into very low, low, medium, high, and very high.

Sensitivity to biophysical hazards was the average of population density index and the protected natural areas index. The population density index was weighted by 0.70 because population dynamics are an important driver of ecosystem disturbance. The protected natural areas index was calculated using QGIS with the vector data of the protected natural areas decreed within the study area.

Socio-environmental pressures were estimated as the availability of ecosystem services related to spatio-temporal vegetation cover changes due to human activities. Data on forest cover loss by the municipality were analysed using the global forest cover change model (HANSEN ET AL., 2013).

2.5. Spatial delimitation and characterization of the socio-ecological system

The cartography of the SES was generated at a scale of 1:250,000 with the QGIS program. The following vector data were integrated: state and municipal limits, land use and vegetation, climate, forest cover, population density, indigenous population, land ownership, protected natural areas and biophysical hazards. Vector data were obtained of Mexican government institutions such as National Institute of Statistic and Geography, National Disaster Prevention Centre and The National Commission for the Knowledge and Use of Biodiversity.

The SESI and its components (SER and SEP) were mapped using vector data of the limits of the study area. SESI values were integrated as a data layer in txt format. The SESI was categorized based on natural breaks; classes were generated based on natural data similarity, thereby maximizing the differences between the eight classes selected.

2.6. Spatial correlation analyses

A spatial autocorrelation analysis was conducted with the results obtained for the SESI and its components (SER and SEP). The local Moran index (ZHANG ET AL., 2021) was used to identify the location of spatial clusters with Queen order two and Euclidean distance, using GeoDa v. 1.20.0.20 (2022). The index values range from 1 to −1, where values close to 1 indicate greater spatial concentration. The cartographic representation was obtained using the LISA method (local index of spatial association), which decomposes the Moran index into categories and verifies the significance of each spatial unit (ANSELIN, 1995). The LISA method was used to locate statistically significant clusters of neighbourhood municipalities with similar values and neighbourhoods with dissimilar values of SESI and their components. LISA classifies values according to their dispersion in the four quadrants of a two-dimensional plane:

– High-high (hotspot); spatial units with values above the average and with neighbours that also have high-percentage values.
– Below-below (coldspot); spatial units with values below the average and with neighbours that also have below-percentage values.
– Below-high; spatial units with low values (below the average) with neighbours with high-percentage values (above the average).
– High-below; spatial units with high values (above the average) with neighbours with low-percentage values (below the average).

2.7. Statistical analysis

A generalized linear model (GLM) was fitted to analyse the effect of socio-ecological variables on SESI. Only 27 standardized variables (values between 0 and 1) were considered to perform a GLM (Table 1). Previously, 12 variables that were significantly correlated with others were discarded. SESI was the dependent variable. The model was built using a stepwise algorithm with a backward option using statistical software SYSTAT (SYSTAT, 2008). This option automatically eliminates variables according to the tolerance criterion (0.05) and confidence interval (95%). Tolerance prevents the entry of a variable that is highly correlated with the independent variables already included in the model. In addition, to select the best model, the algorithm considered the criteria of parsimony (fewer number of explanatory variables), and Akaike criterion (AIC) (statistical parameter to select models by balancing goodness of fit and complexity, penalizing overfitting; lower AIC values indicate better model performance).

The indigenous population (number of inhabitants) per municipality was correlated with SESI and its constituent parameters. Due to the lack of normality of the data, Spearman correlation tests were performed.

3. Results

3.1. State of socio-ecological systems

Socio-ecological status index (SESI) values had a high variation among municipalities, with a range from - 0.244 to 0.361 and a mean of 0.063 (S.D. = 0.17). The SESI average did not differ significantly from 0 ($t = 1.994$, $p = 0.05$). Eight municipalities had negative values, most had values near 0; the 75th percentile was 0.176. Only two municipalities, Eloxochitlán and Xochicoatlán, had SESI values greater than 0.3. For Eloxochitlán, the SESI value was a consequence of its high ecological integrity (0.685), low sensitivity to hazards (0.112), and minor changes in the availability of ecosystem services (0.004) (Table 2). For Xochicoatlán, ecological integrity (0.630), social integrity (0.717), low sensitivity (0.156), and little change in the availability of ecosystem services (0.010) stood out. Municipalities with a lower SESI value, such as Pisaflores, experienced an intense change in the availability of ecosystem services, high sensitivity, and low social integrity (Table 2). The municipality of Huazalingo had the lowest ecological integrity and high sensitivity. Huehuetla, the municipality with the lowest SESI value, had low ecological integrity, relatively low social integrity, and high exposure to biophysical hazards, high sensitivity, and substantial changes in the availability of ecosystem services (Table 2).

Table 2. Estimated SESI (socio-ecological status index) parameters for 28 municipalities in the central-eastern zone of the Sierra Madre Oriental. SER = socio-ecological resilience, EBH = exposure to biophysical hazards, SBH = sensitivity to biophysical hazards, AES = availability of ecosystem services, SEP = socio-ecological pressures, SESI = socio-ecological status index. *Municipalities from Veracruz State

Municipality	Integrity			SER	EBH	SBH	AES	SEP	SESI
	Social	Governance	Ecological						
Eloxochitlán	0.613	0.408	0.685	0.569	0.507	0.112	0.004	0.208	0.361
Xochicoatlán	0.717	0.409	0.630	0.585	0.513	0.156	0.010	0.226	0.359
San Agustín Metzquititlán	0.887	0.370	0.298	0.518	0.356	0.312	0.003	0.224	0.295
Tianguistengo	0.450	0.434	0.516	0.466	0.391	0.234	0.033	0.219	0.247
Molango de Escamilla	0.806	0.309	0.330	0.482	0.555	0.258	0.022	0.278	0.203
Juárez Hidalgo	0.499	0.358	0.264	0.374	0.433	0.083	0.014	0.177	0.197
Zacualtipán de Ángeles	1.000	0.388	0.411	0.599	0.494	0.722	0.038	0.418	0.182
Tlanchinol	0.375	0.607	0.639	0.540	0.522	0.463	0.129	0.371	0.169
Tlahuiltepa	0.411	0.426	0.296	0.378	0.555	0.034	0.062	0.217	0.161
Metztitlán	0.680	0.377	0.415	0.490	0.692	0.384	0.000	0.359	0.132
Jacala de Ledezma	0.593	0.399	0.333	0.442	0.801	0.126	0.015	0.314	0.128
La Misión	0.365	0.396	0.208	0.323	0.441	0.171	0.040	0.217	0.106
Calnali	0.559	0.442	0.128	0.377	0.478	0.357	0.037	0.291	0.086
Lolotla	0.589	0.379	0.135	0.368	0.612	0.231	0.032	0.292	0.076
Huayacocotla	0.488	0.516	0.333	0.446	0.316	0.168	0.635	0.373	0.073
Agua Blanca de Iturbide	0.605	0.345	0.061	0.337	0.410	0.407	0.007	0.275	0.062
Chapulhuacán	0.434	0.459	0.281	0.391	0.495	0.478	0.080	0.351	0.040
San Bartolo Tutotepec	0.368	0.546	0.119	0.344	0.713	0.210	0.035	0.320	0.025
Zacualpan	0.261	0.382	0.188	0.277	0.288	0.081	0.389	0.253	0.024
Tenango de Doria	0.534	0.435	0.170	0.380	0.592	0.479	0.006	0.359	0.021
Tepehuacán de Guerrero	0.279	0.582	0.214	0.358	0.515	0.429	0.141	0.362	-0.004
Zontecomatlán	0.163	0.418	0.232	0.271	0.187	0.269	0.408	0.288	-0.017
Ilamatlán	0.014	0.368	0.098	0.160	0.337	0.408	0.032	0.259	-0.099
Texcatepec	0.000	0.358	0.099	0.152	0.418	0.242	0.324	0.328	-0.176
Tlachichilco	0.291	0.382	0.035	0.236	0.588	0.203	0.475	0.422	-0.186
Pisaflores	0.369	0.418	0.455	0.414	0.405	0.486	1.000	0.630	-0.217
Huazalingo	0.392	0.412	0.000	0.268	0.523	0.585	0.372	0.494	-0.226
Huehuetla	0.373	0.524	0.085	0.327	0.766	0.520	0.427	0.571	-0.244

Socio-ecological resilience (SER) was relatively high for the study area, with an average of 0.388 (S.D. = 0.117); 75th percentile value was 0.478. Texcatepec and Llamatlán had the lowest SER values, with 0.15 and 016, respectively. Significant differences were recorded between the SER components ($H = 16.18$, $p < 0.000$). Ecological integrity had significantly the lowest mean ($\bar{X} = 0.273$, S.D. = 0.186) compared to social integrity ($\bar{X} = 0.468$, S.D. = 0.231), and ecological integrity ($\bar{X} = 0.423$, D. = 0.071). On the other hand, the socio-ecological pressures (SEP) range was from 0.177 to 0.63, and the mean was 0.324 (S.D. = 0.108); this value was significantly different from 0 ($t = 15.8$ $p < 0.000$). SEP components differed significantly ($H = 33.05$ $p < 0.000$). Exposure to biophysical hazards was higher ($\bar{X} = 0.496$, S.D. = 0.142) than the sensitivity to biophysical hazards ($\bar{X} = 0.307$, S.D. = 0.172), while the change in availability of ecosystem services had the lowest values ($\bar{X}$ = 0.170, S.D. = 0.244).

SER ranged from 0.152 to 0.599 ($\bar{X}$ = 0.388, S.D. = 0.117), and SEP from 0.177 to 0.630 ($\bar{X}$ = 0.324, S.D. = 0.108). The municipalities with the lowest resilience were concentrated in the south-eastern part of the study area, while the highest values were in the central area (Fig. 3). SEP, unlike SER, had a homogeneous distribution. The municipality of Pisaflores, located in the extreme north of the study area, had the highest value of sensitivity to biophysical hazards (0.630). Most municipalities (82%) had SER values less than 0.373.

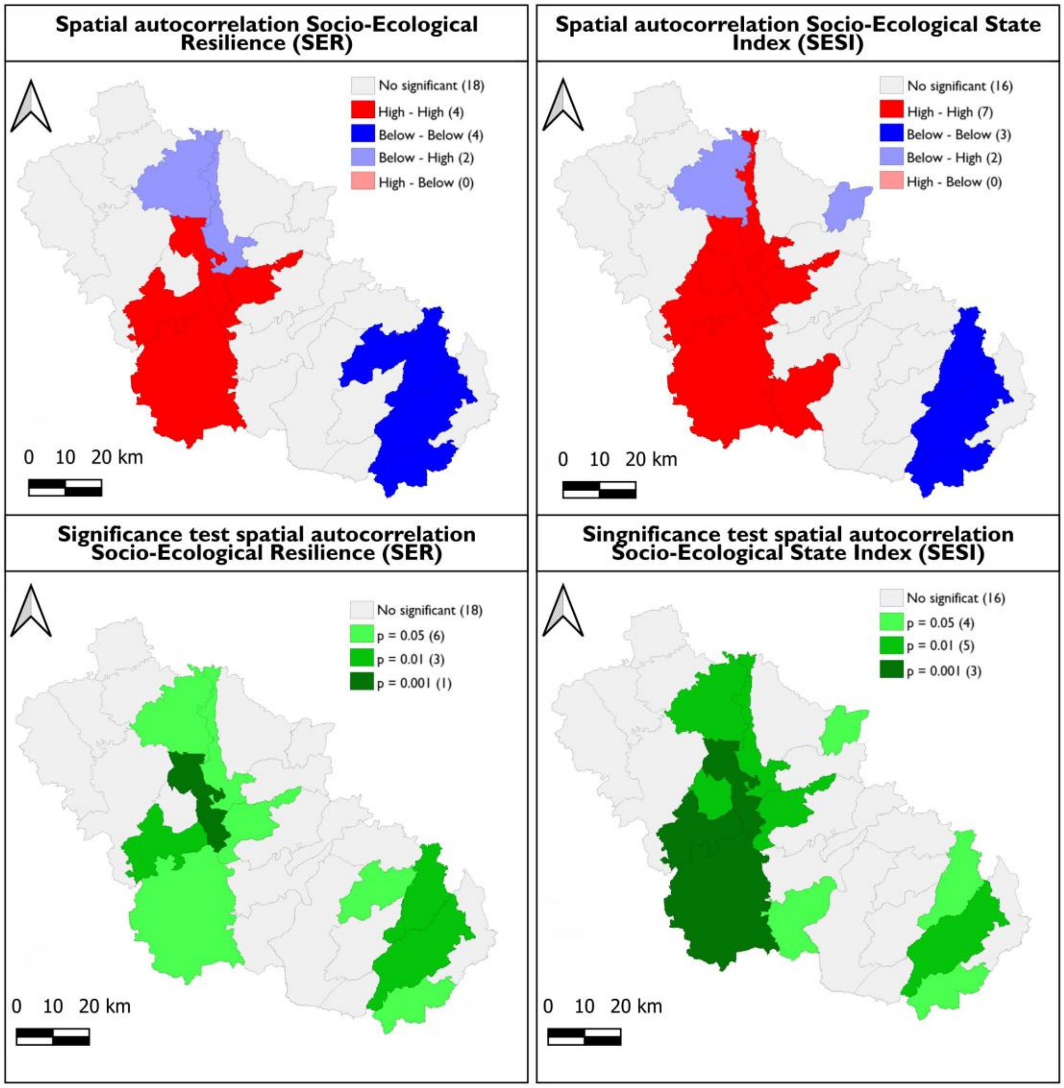

Fig. 3. Municipalities values of the Status of Socio-ecological index (SESI), Socio-Ecological Resilience (RES), and Socio-Ecolo9gical Pressures (SEP) in the central-eastern area of the Sierra Madre Oriental, Mexico

Spatial autocorrelation of SESI values

The spatial autocorrelation analysis revealed interesting patterns. The SESI (IM = 0.165) and the SER (IM = 0.114) values showed significant spatial correlation. In the SEP component of SESI, there was no significant spatial correlation (IM = −0.002). A hotspot for SESI was identified in the central zone of the study area, occupying 29 % of the total study area (Fig. 4, Table 3), where the municipalities of Eloxochitlán, Juárez Hidalgo, Lolotla, Metztitlán, Molango de Escamilla, San Agustín Metzquititlán and Xochicoatlán are located. On the other hand, a coldspot in the south was identified with 9.96 % of the total study area, where the municipalities of San Bartolo Tutotepec, Tenango de Doria and Tlachichilco were located (Fig. 4, Table 3).

With respect to SER, both hotspot and coldspot areas were located similarly to the SESI results (Fig. 4). However, the area of both the hotspot and coldspot were slightly smaller than the result obtained with SESI (Table 3). Central-eastern municipalities Eloxochitlán, Metztitlán, Molango de Escamilla and Xochicoatlán municipalities were grouped as a hotspot. While south municipalities, San Bartolo Tutotepec, Tlachichilco, Tenango de Doria and Texcatepec were grouped in the coldspot area (Fig. 4).

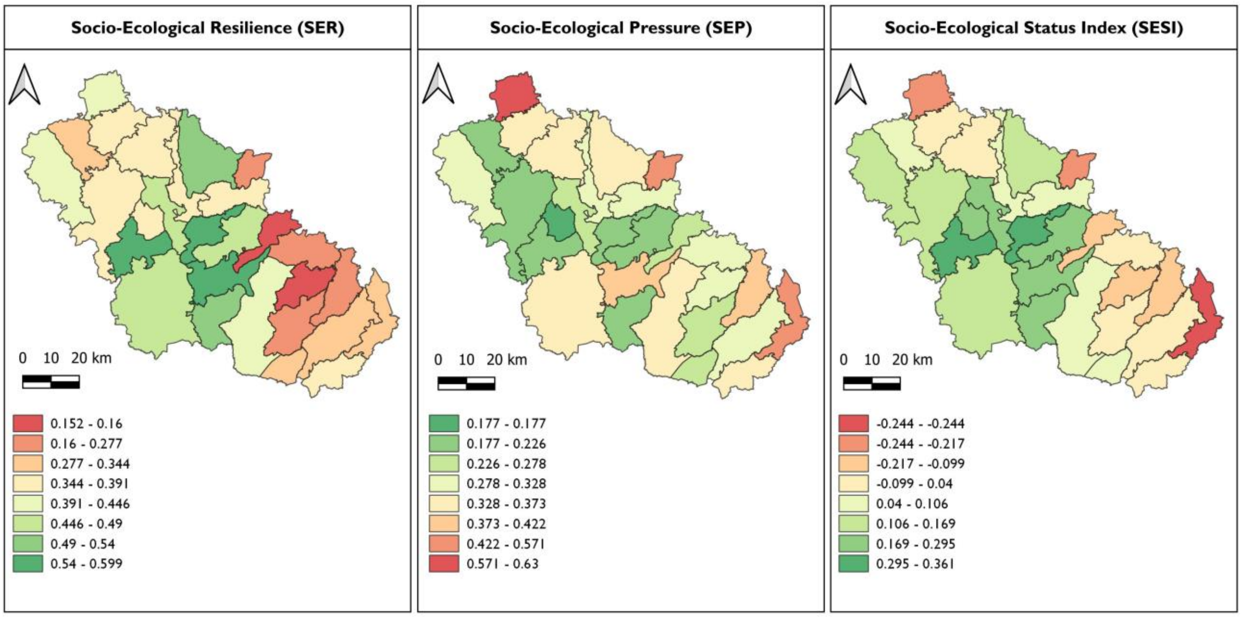

Fig. 4. Spatial auto-correlation using the Moran index according to the Status of Socio-ecological index (SESI) values and the resilience component (SER). The hotspots are shown in red (high-high) and the coldspots shown in blue (below-below)

Table 3. The Socio-ecological status index (SESI) and the Socio-ecological resilience (SER) cluster area determination. Hotspot (high-high) and Coldspot (below-below) areas were considered

	Cluster classification	Area [ha]	Percentage of total area
SESI	High-high (Hotspot)	221797.16	29.02
	Below-below (Coldspot)	76177.62	9.96
	Below-high	45480.02	5.95
	No significant	420654.42	55.07
SER	High-high (Hotspot)	168424.92	22.04
	Below-below (Coldspot)	95702.55	12.52
	Below-high	52455.35	6.86
	No significant	447526.39	58.58

3.2. Generalized linear model

The model that best explained the variance of the SESI was made up of six variables, most of which were from the resilience component and only one from the socio-ecological pressures component. The estimated model had an AIC value of −77.7 and a multiple R^2 of 0.929 (S.E. = 0.053).

Governance variables included in the model had the highest fit values (R^2 = 1- tolerance), such as initiatives approved by the councils and indigenous population, with determination coefficients of 0.292 and -0.179, respectively (Table 4). In the case of the indigenous population, the coefficient was negative but with a low value, which implies that the SESI decreases slightly in the municipalities with a greater presence of indigenous people. Among the variables of the ecological integrity subcomponent, the environmental services index contributed the least to the model's adjustment. In contrast, the change in the availability of environmental services was the only variable representing the SEP component and showed the greatest intensity of change in SESI, as it had the highest coefficient (Table 4).

Municipalities with a larger indigenous population had higher biophysical hazards (SBH) ($rs = 0.554$, $p = 0.002$). The SESI value decreased significantly as the indigenous population size increased ($rs = - 0.59$, $P < 0.000$), the same occurred with resilience ($rs = - 0.389$, $p = 0.04$). Social integrity, an important component of resilience, decreased as the Indigenous population increased ($rs = - 0.538$, $p = 0.003$), while governance increased ($rs = 0.402$, $p = 0.03$).

Table 4. Generalized Linear Model variables with significant effect on the Status of Socio-ecological 9index (SESI) in the central-eastern zone of the Sierra Madre Oriental, Mexico. SER = Socio-Ecological Resilience, SEP = Socio-Ecological Pressures

SESI component	Effect	Coeff.	S. E.	Tolerance	t	p-value
SER (gobernace)	Native population	-0.179	0.035	0.465	-5.159	>0.01
SER (gobernace)	NGOs	-0.123	0.047	0.494	-2.605	0.016
SER (gobernace)	Initiatives approved by the councils	0.292	0.05	0.421	5.824	>0.01
SER (gobernace)	Personal health	0.283	0.031	0.675	9.058	>0.01
SER (ecological integrity)	Environmental services value index	0.357	0.043	0.814	8.34	>0.01
SEP (socio-environmental pressures)	Change in availability of environmental services	-0.372	0.042	0.652	-8.819	>0.01

4. Discussion

The socio-ecological systems in the southern zone of the Sierra Madre Oriental (SMO) were poor, as expressed by a low Socio-ecological status index (SESI). This result contrasts with those obtained elsewhere in the world, where the highest values occurred in Australia (SESI = 0.569) and Canada (SESI = 0.498) (Estoque & Murayama, 2017). In general, the results of this study were similar to the SESI for Mexico, because of the fact that a large part of the country suffers from marginalization and low human development (Martínez-Martínez & Rodríguez-Brito, 2020). Mexico, a multicultural country, faces historical lags, which are reflected in lower status of SESs where there is a larger indigenous population.

The impacts of climate change and deforestation are the main pressure factors on SESs (Gonzalez-Redin et al., 2019). In the SMO, deforestation is a continuous process, reducing forest area implies the loss of ecosystem services, such as water (Leija-Loredo et al., 2018). Municipalities with the largest indigenous populations tend to exhibit a lower percentage of forested land, as these territories are primarily located in lowland areas historically dedicated to livestock farming since the colonial period. Thus, forest loss has not been due to the indigenous presence, *per se*. On the other hand, temperature and drought have increased within the study area (Castelán-Lorenzo & Navarrete-González, 2022).

Governance needs improvement due to almost no citizen participation in decision-making, the low number of agreements in the councils, and the poor coverage of public services. Civil participation, particularly that of indigenous citizens, is key to social development, as it involves inherited knowledge and capabilities essential to adapt, mitigate, and minimize threats (Sahoo et al., 2022). In Latin America, the link between rural communities and institutions is scarce, which has exacerbated marginalization and lack of protection, even ignoring the traditional possession of their lands (Sahoo et al., 2022). Therefore, to increase social progress and the protection of the territory, it is necessary to improve the governance of rural and indigenous communities (Sahoo et al., 2022).

The spatial correlation of SESI and SER detected in the municipalities resulted from their favourable socio-ecological characteristics, such as a low incidence of poverty, human development, high forest cover, and protected natural areas. In general, SESI was low for the study area. However, a hotspot was identified in the central zone where the majority of the municipalities with the highest socio-ecological status are located. While in the southern zone in the Otomí-Tepehua mountain range, a coldspot was identified with the municipalities with the lowest values for both SESI and SER. A coldspot represents critical areas of attention to generate public policies that favour increasing resilience and thus the values of SESI. For example, to increase connectivity between municipalities because it is essential for access to social services, employment, and other basic necessities. The municipalities comprising the coldspot face communication difficulties, as landslides frequently disrupt road access, especially during the winter months. In the SESI hotspots, municipalities are connected by the federal highway, which facilitates access to the major economic centre, including jobs, and businesses. Municipalities along this highway exhibited higher resilience values compared to more remote ones, forming a cluster within a SER hotspot. It is related with historical silver mining that allowed the early development of the infrastructure.

The generalized linear model revealed key indicators that could contribute to increased resilience if appropriately addressed. The first of these indicators is the index of change in the availability of ecosystem services, which is directly related to deforestation in addition to the associated effects such as loss of biodiversity, soil contamination, and water bodies that have contributed to the degradation of ecosystem services (Monterroso-Rivas et al., 2016). In general, over-exploitation of resources has contributed to marginalization and social backwardness, presenting a positive relationship with deforestation (Ellis et al., 2021). The ecosystem services valuation index is another important indicator from an economic point of view (Kaiser et al., 2023). In Mexico, the Payment for Environmental Services program is the main stimulus to promote conservation and reduce the conversion of forest cover. However, its scope has been limited (Chagoya & Iglesias-Gutiérrez, 2009). In the study area, municipalities were identified as receiving greater benefits from paying for hydrological and biodiversity services; however, carbon capture has not been considered (Leija-Loredo et al., 2018). Government resources for environmental services are insufficient, and the benefit distribution is inequitable (Izquierdo-Tort et al., 2022). One of the most important indicators was the indigenous population, since their ways of life and political ontologies are associated with belonging to their territories (Dow, 2005). Although indigenous communities are considered to be highly resilient (Ford et al., 2020), in the SMO, they face limitations such as discrimination, racism, social deprivation, and segregation due to the lack of support for their economies (Wies et al., 2022).

The size of the indigenous population had a negative effect on resilience and, in particular, on Social Integrity. These results reflect the lack of services, poverty, and marginalization that indigenous peoples have suffered since the conquest (Norton-Smith, 2016). Furthermore, in the area, power pressures from local hegemonic groups have caused the displacement of indigenous people to increasingly inaccessible territories. Although indigenous knowledge is vast, encompassing ecological processes as well as governance (Jenssen et al., 2022), it has not been taken into account in territorial management. This is largely because Municipal policies are typically dictated by federal or state government authorities.

Enhancing resilience and improving SESI status requires institutional efforts to focus on bettering services and quality of life for indigenous communities (Ford et al., 2020; Schlingmann et al., 2021). Urgent actions are needed to strengthen communication, health, education, economy, and indigenous participation in decision-making processes to reduce their vulnerability to challenges like climate change. Indices used to estimate socio-ecological condition also allow for evaluating the effect of disturbances and the resilience capacity of the SESs, making them valuable tools for policy-making and decision-making (Brousmiche et al., 2020). Additionally, these indices facilitate comparisons of future scenarios where management strategies are applied, thereby establishing a foundation for comprehensive policies. In this study, regional scale analysis revealed spatial patterns of SES conditions at the municipal level, which is particularly useful for identifying priority areas for interventions.

5. Conclusions

The diagnosis of SES in the Sierra Madre Oriental, based on the SESI index, reveals a generally low level of ecological and social integrity. This condition is primarily characterized by limited governance, high marginalization, low human development, considerable exposure and sensitivity to biophysical hazards, and strong pressures on the availability of ecosystem services. These results underscore the need to implement strategies that strengthen socio-ecological resilience in order to reduce vulnerability and withstand extreme events that may put the population at risk.

Two indicators had the greatest impact on the poor SES performance: governance and the proportion of the indigenous population. Both represent key variables that require attention. In the case of governance, the study recorded a lack of support for community management capacities and a low number of civil society organizations – two aspects that are feasible to address in the short term. On the other hand, a higher percentage of the indigenous population was associated with reduced socio-ecological integrity and resilience, reflecting conditions of poverty and low human development. Support for indigenous communities remains an unresolved historical debt. Socio-ecological resilience, as a fundamental component of SES, could be significantly enhanced through public policies targeting indigenous communities, particularly in areas such as education, health, and livelihood.

Spatial analyses revealed a coldspot characterized by significant clustering of low SESI values, highlighting critical areas for urgent socio-environmental management – particularly in the south-eastern municipalities of San Bartolo Tutotepec, Tenango de Doria, and Tlachichilco. Although all SES assessed at the municipal level require attention, the analyses also detected a hotspot in the north-central region, with a cluster of municipalities exhibiting above-average SER and SESI values.

Overall, the findings emphasize the urgency of implementing integrated management strategies that consider socio-ecological heterogeneity, while promoting adaptation and mitigation in highly vulnerable contexts. Particular attention should be given to SES in municipalities with large indigenous populations and high environmental risk.

Finally, the SESI proved to be a useful tool for comparing different socio-ecological systems and identifying priority areas for more effective policy interventions aimed at increasing socio-ecological resilience and addressing socio-environmental pressures more efficiently. The lack of sufficient data on the SER sub-components prevents downscaling to the local level and the generation of natural system boundaries. Nevertheless, using municipal information as the basic operational unit allowed for the assessment of general conditions in the study area and provided a foundation for understanding socio-environmental inter-relations at the local level.

Acknowledgement

We would like to thank Margaret Schroeder for correcting English grammar and spelling.

References

Anselin L. 1995. Local indicators of spatial association – LISA. *Geografical Analysis*, 27: 93–115.

Ávila S., Espejel I. 2020. *Resiliencia de socio-ecosistemas costeros*. Universidad Nacional Autónoma de México, México.

Battamo A.Y., Varis O., Sun P., Yang Y., Oba B.T., Zhao L. 2021. Mapping socio-ecological resilience along the seven economic corridors of the Belt and Road Initiative. *Journal of Cleaner Production*, 309: 127341.

Berkes F. Folke C. 1998. Linking social and ecological systems for resilience and sustainability. [in:] F. Berkes, C. Folke (eds.), *Linking social and ecological systems: management practices and social mechanisms for building resilience*. Cambridge University Press, Cambridge, UK: 1–26.

Biggs R., Clements H.S., Cumming G.S., Cundill G., De Vos A., Hamann M., Luvuno L., Dirk J., Selomane O., Blanchard R., Cockburn J., Dziba L., Esler K.J., Fabricius C., Henriksson R., Kotschy K., Lindborg R., Masterson V.A., …, Reyers B. 2022. Social-ecological change: insights from the Southern African Program on Ecosystem Change and Society. *Ecosystem and People*, 18: 447–468.

Boege E. 2008. *El patrimonio biocultural de los pueblos indígenas de México: hacia la conservaciónin situ de la biodiversidad y agrodiversidad en los territorios indígenas*. Instituto Nacional de Antropología e Historia, México.

Bollettino V., Alcayna T., Dy P., Vinck P. 2017. Introduction to socio-ecological resilience. [in:] S.L. Cutter (ed.), *Oxford Research Encyclopedia of Natural Hazard Science*. University Press, Oxford, U.K.

Boschma R. 2015. Towards an evolutionary perspective on regional resilience. *Regional Studies*, 49, 5: 733–751.

Brand P., Dávila, J.D. 2022. Resistances in the Resilient City: Medellín y Cali en debate. *Cities*, 120: 103457.

Bristow G. 2010. Resilient regions: re-'place'ing regional competitiveness. *Cambridge Journal of Regions, Economy and Society*, 3, 1: 153–167.

Brousmiche D., Occelli F., Genin M., Cuny D., Deram A., Lanier C. 2020. Spatialized composite indices to evaluate environmental health inequalities: Meeting the challenge of selecting relevant variables. *Ecological Indicator*, 111: 106023.

Castelán-Lorenzo C.L., Navarrete-González M. 2022. Cambio climático y afectaciones en la franja de condensación del bosque de niebla en la sierra Otomí-Tepehua, Hidalgo, México. *Current Topic in Agronomic Science*, 2: 23–29.

Cervantes V., Gama J.E., Roldán I.E., Aragon I.E., Hernández-Cárdenas G. 2014. Bases para Implementar Estrategias de Restauración: El Sistema Socio-Ecológico San Nicolás Zoyatlán (Guerrero, México). *Terra Latinoamericana*, 32: 143–159.

Chagoya J.L., Iglesias-Gutiérrez L. 2009. Esquema de pago por servicios ambientales de la Comisión Nacional Forestal, México. [in:] Sepulveda C.J., Ibrahim M. (ed.) *Políticas y sistemas de incentivos para el fomento y adopción de buenas prácticas agrícolas como medida de adaptación al cambio climático en América Centra*. CATIE, Costa Rica: 189–203.

Chu E., Anguelovski I., Roberts D. 2021. Beyond bouncing back? Comparing and contesting urban resilience across cities. *Cities*, 117: 103347.

CONANP-GIZ. 2013. *Programa de adaptación al cambio climático región central de la Sierra Madre Oriental*. Tlalpan, México.

Cretney R. 2014. Resilience for whom? Emerging critical geographies of socio-ecological resilience. *Geography Compass*, 8, 9: 627–640.

De Garine-Wichatitsky M., Binot A., Ward J., Caron A., Perrotton A., Ross H., Quoc H.T., Valls-Fox H., Gordon I.J., Promburom P., Ancog R., Kock R.A., Morand S., Chevalier V., Allen W., Phimpraphai W. Echaubard P. 2021. Health in and "Health of" social-ecological systems: A practical framework for the management of healthy and resilient agricultural and natural ecosystems. *Frontiers in Public Health*, 8: 616328.

De la Torre-Valdez H.C., Moreno-Vázquez J.L. 2019. Resiliencia del Sistema Socio Ecológico en la región subcuenca baja Río Sonora. *Estudios Sociales*, 29: 2–36.

Dow J.W. 2005. The Sierra Ñähñu (Otomí). [in:] A.R. Sandstrom, E.H.G.A. Valencia (eds.), *Native Peoples of the Gulf Coast of Mexico*. University of Arizona Press.

Elekes Z., Tóth G., Eriksson R. 2024. Regional resilience and the network structure of inter-industry labour flows. *Regional Studies*, 58, 12: 2079–2095.

Ellis E.A., Navarro-Martínez A., García-Ortega M. 2021. Drivers of forest cover transitions in the Selva Maya, Mexico: Integrating regional and community scales for landscape assessment. *Land Degradation & Development*, 32: 3122–3141.

Eraydin A. 2016. Attributes and characteristics of regional resilience: Defining and measuring the resilience of Turkish regions. *Regional Studies*, 50, 4: 600–614.

Estoque R.C., Murayama Y. 2014. Social–ecological status index: A preliminary study of its structural composition and application. *Ecological Indicators*, 43: 183–194.

Estoque R.C., Murayama Y. 2017. A worldwide country-based assessment of social ecological status (c. 2010) using the social-ecological status index. *Ecological Indicators*, 72: 605–614.

Folke C. 2006. Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environmental Change*, 16: 253–267.

Ford J.D., King N., Galappaththi E.K., Pearce T., McDowell G., Harper S.L. 2020. The resilience of indigenous peoples to environmental change. *One Earth*, 2: 532–543.

Gonzalez-Redin J., Gordon I.J., Hill R., Polhill J.G., Dawson T.P. 2019. Exploring sustainable land use in forested tropical social-ecological systems: A case-study in the Wet Tropics. *Journal of Environmental Management*, 231: 940–952.

Hansen M.C., Potapov P.V., Moore R. 2013. High-Resolution Global Maps of 21 st-century Forest Cover Change. *Science*, 342: 850–853.

Holling C.S. 1973. Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, 4: 1–23.

INEGI. 2020. *Censo de Población y Vivienda 2020*. México.

Izquierdo-Tort S., Corbera E., Martin A., Lillo J.C., Dupras J. 2022. Contradictory distributive principles and land tenure govern benefit-sharing of payments for ecosystem services (PES) in Chiapas, Mexico. *Environmental Research Letters*, 17: 055009.

Jessen T.D., Ban N.C., Claxton N.X., Darimont C.T. 2022. Contributions of Indigenous Knowledge to ecological and evolutionary understanding. *Frontiers in Ecology and the Environment*, 20: 93–101.

Kaiser J., Krueger T., Haase D. 2023. Global patterns of collective payments for ecosystem services and their degrees of commodification. *Ecological Economics*, 209: 107816.

Khan A., Didkowsky N., Ungar M. 2025. The Social Ecology of Resilience in Rural Contexts. [in:] U. Kumar (ed.), *The Routledge International Handbook of Psychosocial Resilience*. Routledge, New York: 75–90.

Kumar P., Fürst C., Joshi P.K. 2021. Socio-ecological systems (SESs) – identification and spatial mapping in the central Himalaya. *Sustainability*, 13, 14: 7525.

Leija-Loredo E.G., Pavón N.P., Sánchez-González A., Rodríguez-Laguna R., Ángeles-Pérez G. 2018. Land cover change and carbon stores in a tropical montane cloud forest in the Sierra Madre Oriental, Mexico. *Journal of Mountain Science*, 15: 2136–2147.

Li T., Dong Y., Liu Z. 2020. A review of social-ecological system resilience: Mechanism, assessment and management. *Science of the Total Environment*, 723: 138113.

Martínez-Martínez O.A., Rodríguez-Brito A. 2020. Vulnerability in health and social capital: a qualitative analysis by levels of marginalization in Mexico. *International Journal for Equity in Health*, 19: 1–10.

Martín-López B., Palomo I., García-Llorente M., Iniesta-Arandia I., Castro A.J., Del Amo D.G., Gómez-Baggethun E., Montes C. 2017. Delineating boundaries of social-ecological systems for landscape planning: A comprehensive spatial approach. *Land Use Policy*, 66: 90–104.

Masik G. 2022. The concept of resilience: Dimensions, properties of resilient systems and spatial scales of resilience. *Geographia Polonica*, 95, 4: 295–310.

McCool S.F., Mandic, A. 2025. A social-ecological systems perspective on working toward resilience in nature-based tourism planning. *Tourism Planning & Development*, 22: 632-654.

Merlo-Galeazzi A., Avila-Foucat V.S., Perevochtchikova M. 2024. Analysis of the watershed social–ecological system trajectory in Copalita-Huatulco, Mexico: The impact of drivers on hydrological ecosystem services. *Ambio*, 53: 1797–1812.

Monterroso-Rivas A.I., Ramírez-García A.G., Gómez-Díaz J.D., Velázquez-Juárez Y., Rendón-Medel R. 2016. Changes in future water availability in a mesophyl mountain forest in Mexico. *Interciencia*, 41: 266–272.

Noble M.M., Harasti D., Pittock J., Doran B. 2021. Using GIS fuzzy-set modelling to integrate social-ecological data to support overall resilience in marine protected area spatial planning: A case study. *Ocean & Coastal Management*, 212: 105745.

Norton-Smith K. 2016. *Climate change and indigenous peoples: a synthesis of current impacts and experiences* (Vol. 944). United States Department of Agriculture, Forest Service, Pacific Northwest Research Station. Washington, D.C.

Ostrom E. 2009. A general framework for analyzing sustainability of socio-ecological system. *Science*, 325: 419–422.

Proswitz K., Edward M.C., Evers M., Mombo F., Mpwaga A., Näschen K., Sesabo J. Höllermann B. 2021. Complex socio-ecological systems: translating narratives into Future land use and land cover scenarios in the Kilombero Catchment, Tanzania. *Sustainability*, 13, 12: 6552.

Raskin P.D. 2008. World lines: A framework for exploring global pathways. *Ecological Economics*, 65, 3: 461–470.

Sahoo G., Wani A.M., Swamy S.L., Mishra A., Mane S.P. 2022. Indigenous people activities on ecosystems and sustainable development-a paradigm shift. [in:] U. Chatterjee, Kashyap A., Everard M., Krishna-Panda G., Mahata D. (eds.), *Indigenous People and Nature: Insights for Social, Ecological, and Technological Sustainability*, Elsevier: 3–27.

Schlingmann A., Graham S., Benyei P., Corbera E., Sanesteban I.M., Marelle A., Soleyman-Ford R., Reyes-García V. 2021. Global patterns of adaptation to climate change by Indigenous Peoples and local communities. A systematic review. *Current Opinion in Environmental Sustainability*, 51: 55–64.

Scholz R.W. Binder C.R. 2004. Principles of Human-Environment Systems (HES) Research. *International Congress on Environmental Modelling and Software*, 116: 1–6.

Shamsuddin S. 2020. Resilience resistance: The challenges and implications of urban resilience. *Cities*, 95: 102–409.

Simmie J., Martin R. 2010. The economic resilience of regions: Towards an evolutionary approach. *Cambridge Journal of Regions. Economy and Society*, 3, 1: 27–43.

Souther S., Stuart D., Aslan C. 2025. Traditional harvest systems as models for advancing understanding of dynamics and resilience in socio-ecological systems. *Ecosphere*, 16, 7: e70349.

Sowada T. 2024. Pre- and post-pandemic attitudes toward participation in community initiatives: evidence from Poznań. *Geographia Polonica*, 97, 2: 133–152.

Stotten R., Ambrosi L., Tasser E.I., Leitinger, G. 2021. Social-ecological resilience in remote mountain communities: Toward a novel framework for an interdisciplinary investigation. *Ecology and Society*, 26, 3: 29.

Suárez-Mota, M.E., Villaseñor J.L., López Mata L. 2017. Dominios climáticos de la Sierra Madre Oriental y su relación con la diversidad florística. *Revista Mexicana de Biodiversidad*, 88: 224–233.

Thonicke K., Bahn M., Lavorel S., Bardgett R.D., Erb K., Giamberini M., Reichstein M., Vollan B., Rammig A. 2020. Advancing the understanding of adaptive capacity of social-ecological systems to absorb climate extremes. *Earth's Future*, 8: e2019EF001221.

Turner B., Devisscher T., Chabaneix N., Woroniecki S., Messier C., Seddon N. 2022. The role of nature-based solutions in supporting social-ecological resilience for climate change adaptation. *Annual Review of Environment and Resources*, 47: 123–148.

Ungar M., Koubova A. 2024. The Emerging Science of Multisystemic Resilience: Trade-offs and Transformations in Contexts of Adversity. *Filozofia*, 79, 10: 1174–1185.

Virola R.A., Agtarap K.F.S., Villanueva P.C., Villaruel M.L.C. 2016. *The 2016 elections and the good governance index: performance, promises, or political dynasties?* Philippines Statistics Authority.

Walker B., Holling C.S., Carpenter S.R., Kinzig A. 2004. Resilience, adaptability and transformability in social–ecological systems. *Ecology and Society*, 9, 2: 5.

Wies G., Navarrete-Segueda A., Ceccon E., Larsen J., Martinez-Ramos M. 2022. What drives management decisions and grain yield variability in Mesoamerican maize cropping systems? Evidence from small-scale farmers in southern Mexico. *Agricultural Systems*, 198: 103370.

Wilson G.A., Schermer M., Stotten R. 2018. The resilience and vulnerability of remote mountain communities: The case of Vent, Austrian Alps. *Land Use Policy*, 71: 372–383.

Woodruff S., Bowman A.O´M., Hannibal B., Samsom G., Portney K. 2021. Urban resilience: Analyzing the policies of U.*S.* cities*. Cities*, 121: 103475.

Yang H., Huang J., Liu D. 2020. Linking climate change and socioeconomic development to urban land use simulation: Analysis of their concurrent effects on carbon storage. *Applied Geography*, 115: 102135.

Zhang Y., Lu X., Liu B., Wu D., Fu G., Zhao Y., Sun P. 2021. Spatial relationships between ecosystem services and socio-ecological drivers across a large-scale region: A case study in the Yellow River Basin. *Science of the Total Environment*, 766: 142480.