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Conceptual model of social-ecological resilience in Mexican forests communities

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The social-ecological forest systems of central Mexico are essential for delivering a variety of contributions of nature that benefit both local and global communities, however, these forests are under increasing threat from climate change, market globalization, and outmoded forest policies. This paper examines the resilience of these social-ecological forest systems, focusing on their ability to adapt to such challenges. We utilized the grounded theory method, which combines quantitative and qualitative data from existing literature and empirical knowledge about the structure and functioning of forests and human communities. Then, we developed a dynamic system conceptual model to describe the cause-effect processes of forest disturbances and resilience capacities integrating qualitative interdisciplinary information to establish causal links and adaptive strategies. Our conceptual model identifies forest disturbances threatening Mexican forests, key structural elements and dynamic interactions within these systems, specifically governance system (social processes), contributions of nature (ecological processes), and forest management (social-ecological processes) promoting the resilience. By analyzing the effects of climate change and globalized markets we aimed to uncover the factors that enhance or undermine resilience in these systems, for example, climate change adversely affects species richness, soil properties, and economic diversification, creating a feedback loop that diminishes ecosystem resilience. On the other hand, polycentric governance, biodiversity maintenance, and the control of slow-changing variables like nutrient recycling in forest soils are crucial for long-term forest management. We propose several strategies for enhancing resilience, for example, including the implementation of mixed forest plantations and community nurseries with native species to address climate change impacts. While globalized markets tend to favor the intensification and specialization of timber production, which reduces economic diversification, our research suggests that promoting multi-purpose forest harvesting and preserving other contributions of nature are essential for maintaining biodiversity and supporting local livelihoods.

KEYWORDS

adaptive management, ecological modeling, forest management, social-ecological resilience, contributions of nature

1 Introduction

Temperate and boreal forests play a crucial role in climate regulation, biodiversity conservation and the provision of contributions of nature fundamental to human wellbeing. They also provide a wide variety of benefits and economic income for their human communities (FAO and Food and Agriculture Organization of the United Nations, 2015; Malhi et al., 2014), however, they are receiving more intense and frequent stressors and forest cover has decreased by 0.2%, equivalent to almost 25 million hectares each year since the launch of the 2030 Agenda in 2015. This represents about a quarter of the net forest area loss of nearly 100 million hectares over the past two decades (FAO, 2018; Da Silva, 2017). On the other hand, the impacts of global change, land cover change and outmoded forest policies on the world's forests (loss biodiversity, rapid climate and socio-economic changes, forest fragmentation, pollution, introduction of new pests and diseases) are causing abrupt transitions to other ecosystem states and crossed tipping points into new system configurations (Coleman and Steed, 2009; Crutzen, 2006). Therefore, the vulnerability of social-ecological systems (SES) entails the loss of resistance and resilience (Bonnesoeur et al., 2019). Resilience may be specific in response to a single threat, or it may be general in the face of multiple stressors and uncertain change (Folke, 2006). In a world marked by climate change, biodiversity loss and continued pressure on natural resources, the need to develop strategies that foster resilience is becoming increasingly pressing.

A social-ecological system (SES) is a coupled and adaptive system composed of a biophysical environment and its associated social actors, institutions, and governance mechanisms that together shape, manage, and respond to ecological and environmental changes (Berkes and Folke, 1998). Therefore, we understand forests managed as social-ecological systems and therefore use an integrative approach such as social-ecological resilience. Social-ecological resilience is a term that addresses the capacity of integrated systems of nature and society to resist, adapt and recover from disturbances, changes or crises (Vázquez-González et al., 2021). This concept recognizes the intimate interconnectedness between the social and ecological components of a system, highlighting the need to understand and manage these relationships to promote sustainability. In the social-ecological context, resilience implies the ability of human communities and natural ecosystems to maintain their essential structure and functions, even under conditions of stress or disruption. Resilience focuses not only on resistance to adverse impacts, but also on the ability to effectively adapt and recover after a disruptive event (Garmestani et al., 2013). Key elements of social-ecological resilience include diversity and redundancy in social and ecological systems, capacity for learning and adaptation, effective governance that promotes community participation, and sustainable management of natural resources (González-Quintero and Avila-Foucat, 2020). Social-ecological resilience consists of actively maintaining a diversity of functions and feedbacks, steering systems away from critical thresholds at which they would tip into undesired regimes and increasing the capacity of systems to cope with change (Mahmoudi et al., 2018). We want to measure resilience to take the systems toward more sustainable states. The core of social-ecological resilience is thus (1) to anticipate potentially unwanted shifts in a desired regime and to take actions to prevent them, (2) to maintain a diversity of system elements and feedback interactions that will keep a system within a particular desired regime that provides desired goods and services (González-Quintero and Avila-Foucat, 2020), and (3) to reduce the likelihood of unwanted regime shifts by increasing the ability of the social–ecological system to cope with novel situations (Falk et al., 2022). In summary, socioecological resilience is a holistic approach that seeks to strengthen the capacity of complex systems to cope with challenges and changes, promoting the harmonious coexistence of society and the natural environment in the long term.

Conceptual frameworks and empirical applications can evaluate social-ecological resilience, but challenges remain (Folke et al., 2010; Spears et al., 2015). Conceptual models have facilitated the understanding of complex systems, yet few forest management planning models include elements of social dynamics such as governance or diversification of economic activities in the region. Social-ecological resilience is difficult to implement and quantify in community forest in central Mexico (Carpenter et al., 2009), and we propose this theoretical approach as a strong contribution to the transition toward a more sustainable forest SES (Walker et al., 2002; Yeung and Richardson, 2018). This research poses one central question: how do social, economic and governance components interact with forest management, and contributions of nature and to what extent do they contribute to social-ecological resilience in the temperate forests of central Mexico? We proposed the following specific goals: (1) develop a conceptual model for forest social-ecological to understand the cause-effect processes of forest harvesting in temperate forests, focusing on the resilience and adaptive strategies of these ecosystems in the face of disturbances, (2) identify how critical global drivers threaten the resilience of the forest in central Mexico, and (3) applying a resilience framework to design goals and actions forest management for enhancing resilience capabilities of forest SES. We propose a socioecological framework to analyze resilience as a holistic and integrative approach capable of encompassing the socioecological complexity of forests; also, we identify some management alternatives that would increase socioecological forest resilience to face global change to the main stressors.

2 Methodology

2.1 Data collection

We began by collecting relevant data on the structure and functioning of forest ecosystems, as well as socioeconomic and environmental information related to human communities that depend on these resources. Subsequently, a comprehensive analysis of the available scientific and technical literature, as well as consultations with experts in the field, was carried out to identify the main factors that influence the resilience of forest systems. A systematic literature review was achieved to construct a conceptual framework of SES that navigates social-ecological forest systems toward sustainability by identifying relevant social, economic, and environmental components and using the SES framework concepts as tools for this approach. We adapted the qualitative approach proposed by Tenza et al. (2017). The literature search was conducted to identify the disturbances affecting temperate forests and used academic reference databases, including Science Direct, Web of Knowledge, and Scopus, following the guidelines for systematic reviews proposed by Pullin and Stewart

(2006). The literature review for the temperate forests of Mexico in the last 20 years was carried out following a systematic and exhaustive process. First, the relevant scientific databases and repositories that contained information related to the topic of study were identified. This included academic databases such as Web of Science, Scopus and Google Scholar, as well as institutional repositories and journals specializing in forestry and environmental issues. Once the sources of information were identified, searches were carried out using specific search terms related to the temperate forests of Mexico, forest dynamics, ecological resilience and social and ecological indicators. Based on this information, a conceptual framework was developed that integrated key elements of social-ecological resilience, including aspects related to biodiversity, governance, adaptability and responsiveness to disturbances. This framework was developed through an iterative process of review and feedback, which allowed the identified concepts and relationships to be refined and adjusted (Turner and Robbins, 2008).

The methodology for assessing the resilience of social-ecological systems (SES) follows a structured conceptual process. Initially, we identified the system elements essential for determining resilience capacities, considering both external stressors, such as climate change impacts, and local stressors like forest management practices. The first step in our analysis was to determine if the forest management methods used in these systems allow, limit, or favor the allowance of contributions of nature, using qualitative descriptions and data sources that guided our interpretation. Finally, we collected indicators on the contributions of nature and evaluated resilience capacities, including whether strategies for strengthening resilience were necessary and whether the system had the capacity for adaptation (Figure 1). Once the conceptual framework was established, it was validated by applying it to specific case studies, where its ability to capture and explain the dynamics of forest systems and their resilience to different types of disturbances was evaluated. This validation was carried out using a combination of qualitative and quantitative methods, including spatial data analysis, dynamic systems modeling and interviews with key stakeholders. For the social-ecological characterization, we administered 32 interviews and 77 surveys with the forest rural communities (rural smallholders) plus interviews with external stakeholders from the academic sector (Universidad Autónoma de Tlaxcala, University of Tlaxcala), government agencies (CONAFOR), and members of the timber industry in the region (timber buyers, millyard owners, and furniture manufacturers). Two semi-structured interview formats were used to gather information about ejido history, internal organization, association capabilities within and outside the ejido, and forest management capabilities. Four participatory workshops were also held to understand the transformation perceived by communities from forest harvesting, both in forests and in economic, social, and political factors. Participation in workshops and voice recordings was voluntary, based on informed consent principles (Moriello et al., 2005).

The review of scientific literature made it possible to characterize and contextualize the implementation of forest government programs, instruments, and incentives in the communities studied, as well as to identify global-change factors, threats, hazards, disturbance, and stressors in temperate forests of Mexico. Impacts from change factors were identified following the classification proposed by Bruelheide and Luginbühi (2009) and Heffernan et al. (2014). To this end, we described the level of impact from change factors on threats (rapid and external changes), disturbances (rapid changes within or outside of the system), and stressors (slow changes within the system). A detailed report was prepared that documented the process of constructing the conceptual model, as well as the results obtained from its application to specific case studies. This report included recommendations for the management and conservation of forest ecosystems, as well as suggestions for future research and improvements in the conceptual model of forest resilience (Table 1). On the other hand, inputs from previous research and data recorded in the temperate forest region of central Mexico were used to construct a conceptual model and its change over time. Ecological information (species richness and diversity; vegetation structure and soil nutrients) was collected locally on various plots subjected to different forest practices associated withMethod of Silvicultural Development (MDS), an intensive approach that transforms irregular forests into regular forests through the total harvesting of the tree biomass in plots and the Mexican Method of Irregular Forests (MMBOI), a semi-intensive method that removes only the oldest trees. Social data (governance, institutions, and economics) were gathered from previous research works conducted at the study sites (Table 1).

We focus on assessing the resilience of the forest SESnot only as an abstract concept, but as a practical tool to address specific challenges. We explore the resilience of the system to evaluate the impacts of climate change and current management practices, as well as the resilience of the forest communities that depend on these ecosystems for their livelihoods and well being (Figure 1). In this context we define a quantitative assessment approach that can understand socioecological resilience by analysing the performance of their variables in response to disturbances or stressors. We begin by examining how resilience is defined in this context, focusing on three key aspects: the ability to maintain natural functions and feedback, the prevention of transgression of critical thresholds, and the strengthening of adaptive capacity in the face of change. We describe the key conceptual elements of these systems, building on González-Quintero and Avila-Foucat (2020) work and his holistic approach to address the complexity of society-environment interactions in the forest context. From a social-ecological resilience perspective, forest systems are characterized by dynamic interdependence between biotic and abiotic components, as well as the human influences and activities that shape and modify these ecosystems. We explore how these conceptual elements intertwine and contribute to a holistic understanding of forest systems as complex and dynamic entities. Throughout this analysis, we will examine the fundamental components of forest social-ecological systems according to Quintero's perspective, including biological diversity, ecological cycles, community interactions, management practices, and human perceptions and values associated with these ecosystems. When we talk about the capacity to maintain functions and feedback, we refer resilient forest system must be able to maintain its essential functions and the feedback that enable the provision of contributions from nature. A resilient system that avoids critical thresholds should stay away from critical thresholds that may lead to irreversible changes or severe damage.

Finally, this approach widens the scope and complements insight into the aspects and actions that stakeholders and policy makers should focus on, through our three main identified challenges of climate change, policy and forest management. We also make a theoretical approach by analyzing the disturbances and impacts on

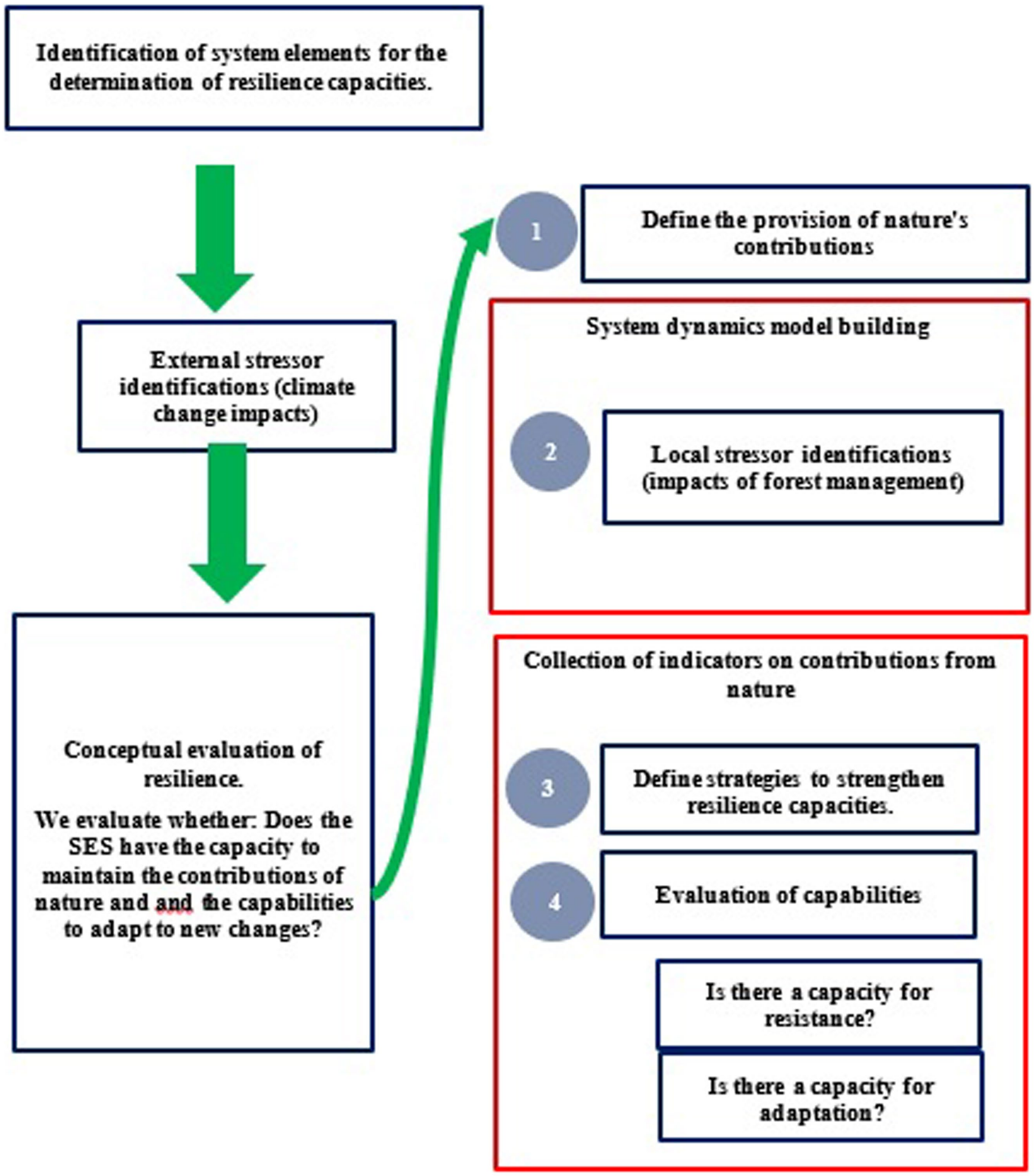

FIGURE 1
Conceptual process for resilience assessment in intensively and semi-intensively managed forest social-ecological systems. It considers the contributions of nature, the impacts of local stressors and climate change, and resilience and adaptive capacities.

forest reported in the literature. By reviewing and synthesizing previous research, we aim to enhance our understanding of how different factors contribute to or hinder resilience in forest social-ecological systems.

3 Results

3.1 Conceptual model of social-ecological resilience

Figure 2 illustrates the complex interplay of factors influencing forest management, categorized into climate change, natural resources, ecosystem conditions and soil fertility, social variables, economic indicators, and infrastructure. Green elements signify climatic variables like precipitation and temperature, which have significant impacts on forest dynamics. Blue elements highlight components differentiated by resource utilization methods, such as standing trees, wood, and policies. Red arrows depict processes ensuring system resilience by maintaining ecosystem functions, avoiding critical thresholds, and enhancing adaptive capacity. Key interactions include the influence of forest area on vegetation, the role of policies and conservation in sustainable management, and socio-economic drivers such as financing programs, income sources and human welfare. The findings do not support a one-way direct relationship between

TABLE 1 Methodological route to build a conceptual model of a dynamic system that aims to understand the cause-effect processes of logging in temperate forests.

1	Definition of	Resilience of what?		
		Objectives to resilience management		
		Several actions can be implemented		
			Literature survey	Early visits and semi-structured interviews
2	Data collection	Factors of change	X	
		Biological and ecological data	X	X
		Socioeconomic data:		The history of communal lands; internal organizational structures; clustering capabilities; forest enterprises; management capacities; markets; natural capital; financial capital; and forest management capacities.
3	Model development:	System dynamics models to assess resilience		
4	Integration of social and ecological components:	Model interactions between social and ecological elements, such as the influence of human activities on forest health. Includes agents representing local communities, government institutions, etc.		

ecosystems and natural resources, instead, the text and diagram indicate that this is an interactive dynamic, where feedback loops between components such as forest area, vegetation species, and standing trees mutually influence each other. On the other hand, socio-economic drivers like financing programs, income sources, and human welfare integrate into these dynamics, further emphasizing the interconnected nature of the system. Forest governance system emerges as a political dynamic, raising questions about the integration of social and economic variables within the governance framework, as it remains unclear how these reside internally within such a system. We focus on assessing the resilience of the forest social-ecological system not only as an abstract concept, but as a practical tool to address specific challenges.

We explore the resilience of the system to the impacts of climate change and current management practices, as well as the resilience of the forest communities that depend on these ecosystems for their livelihoods and wellbeing (Table 2). We describe the key conceptual elements of these systems, building on work of González-Quintero and Avila-Foucat (2020) and his holistic approach to address the complexity of society-environment interactions in the forest context. From a social-ecological resilience perspective, forest systems are characterized by dynamic interdependence between biotic and abiotic components, as well as the human influences and activities that shape and modify these ecosystems. We explore how these conceptual elements intertwine and contribute to a holistic understanding of forest systems as complex and dynamic entities and examine the fundamental components of forest social-ecological systems according to Quintero's perspective, including biological diversity, ecological cycles, management practices, and human perceptions and values associated with these ecosystems. By understanding these conceptual elements, we hope to provide a more complete and holistic view of the complexity of forest systems and the challenges and opportunities they face in a changing world (Table 2). The structural elements of the forest social-ecological system in Mexico were considered at the ejido level and they are divided into ecological (species richness, composition, and diversity, soils); and social (governance system); and their interactions are mentioned (forest management, governance, and the provision of ecosystem services). The interaction between the social benefit of wood harvesting and ecological aspects involves elements such as diversity of wildlife and traded species, carbon pools, soil fertility, and volume and frequency of wood extraction. Within the social system, governance integrates the political stakeholders within the community: the ejidal assembly, forestry technicians, and regulatory authorities responsible at the local level. Finally, the interaction of ecosystem services refers to carbon sequestration, climate regulation, and biodiversity and recreation service. Changes in livelihood strategies are considered mechanisms of adaptability. Changes in forestry practices that have been adopted and improved by communities due to past experiences with disturbances are indicators of adaptability.

3.2 How global markets, climate change, and harvest threaten forest ecosystem resilience

The change in temperature and precipitation patterns under climate change scenarios influences the habitats of wildlife species and affects species composition, primary productivity, and the provision of contributions of nature (Crutzen, 2006). It is estimated that 50% of the area covered by vegetation in Mexico is susceptible to the effects of climate change, with temperate forests being the most sensitive ecosystems, prone to the loss of biodiversity (CONAFOR, 2012). For example, climate change scenarios A2 and B2 suggest that air temperature in the state of Tlaxcala may rise by up to 3°C by the end of the century. However, changes in local climatic conditions may be even greater (Galicia et al., 2015). Changes in rainfall patterns are more uncertain, but scenarios A2 and B2 for 2010–2040 indicate minor changes for most of this century, between-5% and-10%; therefore, drought periods will become increasingly constant. In

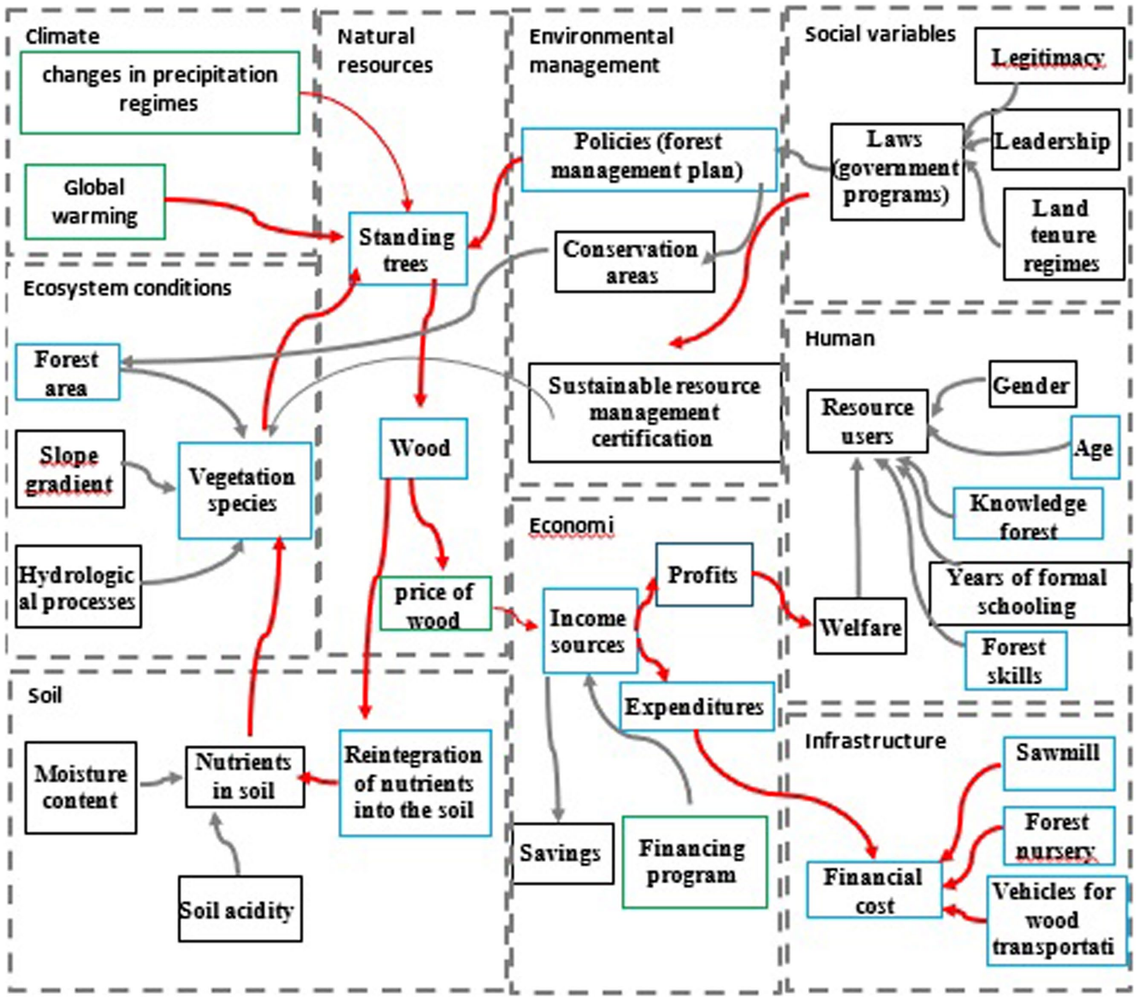

FIGURE 2
System diagram of various factors affecting forest management. The blue components represent those differentiated by the method of resource utilization, while the green components indicate areas where the change factors being tested are expected to have an impact. The red lines represent processes that currently achieve the following: (1) the capacity to maintain the functions and feedbacks that enable the provision of contributions from nature, (2) keeping the system away from critical thresholds, and (3) strengthening the capacity of systems to cope with change.

TABLE 2 Key questions for the definition of forest social-ecological systems.

How resilience is conceptualized?	The forest social-ecological system is resilient if it 1. It has the capacity to maintain the functions and feedbacks that enable the provision of contributions from nature. 2. It keeps the system away from critical thresholds. 3. Strengthens the capacity of systems to cope with change.
Resilience of what?	We assess the resilience of the social-ecological system
Resilience to what?	We assess the resilience to climate change and the impacts of the current management method
Resilience to whom?	Seeking resilience for forest communities

Mexico, current evidence suggests that altitudinal tree lines will move upwards (Galicia et al., 2015); in addition, there will be a reduction in the potential forest establishment areas to several species. There are forecasts of alterations in the frequency and intensity of forest fires, incidence of forest pests, and increased damage to forests from extreme weather conditions such as droughts, floods, and storms (FAO, 2018). For example, in the context the year with the driest conditions has been reported bark beetle outbreaks for four conifer species showed an annual increasing trend: from an average of 38 outbreaks in 2009 to 1,051 in 2021 (Gómez-Pineda et al., 2023). Similarly, In México, the last year's show that fires with an affected area of 500 to 1,000 hectares are frequent almost all over the country, while events of more than 10,000 hectares are rare and concentrated mainly in the northern states, but they make up a large proportion of the total the burn areas annually (Neger et al., 2022) (Table 3).

Globalized markets have boosted the internationalization of companies and accelerated the forms of production. On average, the price of standing wood in the last years has been $55 US dollars per

10.3389/ffgc.2025.1490278

TABLE 3 Summary and integration of social processes that determine the governance of temperate forests in Mexico.

Social or ecological processes to evaluate	Measurement indicators	Indicator definition and delimitation	Evaluation example	Data from:			
				Interviews		Surveys	Literature
				To community	External		
Trust and reciprocity rules	Local institutions	Set of rules in certain contexts that are constructed, agreed upon, and modified by the resource users themselves, essential for the successful management of forest resources (Abel et al., 2006).	The system of communal positions and habits and practices favors values and attitudes related to cooperation, reciprocity, community autonomy, participation, and transparency, within the general ideology of community service (Bray and Merino, 2004).				
	Resolution of conflicts	It refers to disagreements regarding forest harvesting, so that any decisions made by the assembly are accepted and appropriate for the community (Paz, 2014).	Conflicts can be aggravated by the lack of trust in the local authorities; confidence in the assembly potentially supports diversification into more sustainable harvesting practices (Duran, 2009).				
	Resolution mechanisms	These processes can be approximated from proxies such as experience in previous conflicts and collaboration with government institutions or the commissariat. Conflict management is a process or mechanism through which a disadvantaged individual or social group is empowered (Beunen et al., 2017; Duran, 2009)	Strategies for adaptive or sustainable forest management are feasible provided there is an appropriation process or, in its absence, a community negotiation process with other social and institutional stakeholders. In the case of non-agreement, resolution mechanisms gain greater importance (Beunen et al., 2017).				
	Trust in institutions or commissariats	Compliance, trust, and security in external or internal community institutions. Legitimacy means acting with justice, allowing the participation of civil society, meeting its demands, and turning its decisions into public policy (Ostrom, 1978).	The transition toward new forest management strategies is hampered when there is no confidence in proposals from external institutions or in the internal institutions that implement these new and improved strategies. The members of the ejido assembly, the forestry technician, forest harvesting regulatory authorities, and companies or direct timber purchasers participate in a permanent dynamic process that largely depends on the levels of trust between those involved.				

(Continued)

TABLE 3 (Continued)

Social or ecological processes to evaluate	Measurement indicators	Indicator definition and delimitation	Evaluation example	Data from:			
				Interviews		Surveys	Literature
				To community	External		
Networks/forms of civil participation	Decision-making process	Decision-making is an effective process provided the different perspectives are heard	Any decisions made within communities require freedom of expression and association, respect for and strengthening of human rights; the general public should be duly informed about the decisions made and implemented by leaders. Therefore, the ejido commissariat should have the capacity to fulfill its functions, and the sensitivity to take into account the aspirations and needs of citizens (Duran, 2009).				
	Appropriation of practices	Acceptance and understanding of community forest harvesting or productive harvesting practices (Majone, 2005).	In communities that have greater appropriation of practices, the transition to more sustainable practices is more likely. Ignorance of the impacts of management techniques forestalls any improvements (Duran, 2009).				
	Forest knowledge	Data, statistics, impact assessment, and understanding of utilization on forest structure (Balvanera, 2012).	Knowledge of the impacts of harvesting has the potential to shift efforts to more sustainable practices (Brenner, 2018).				
	Inclusion of women and youngsters	The participation of vulnerable groups, but also major groups and groups representing an important labor force, shall be included in the forms, techniques, and understanding of sustainable forest harvesting.	The collaboration, association, and organization of women can diversify forest harvesting activities while lowering the impact on intensive harvesting and adding value to forest products (Brenner, 2018).				
	Participation in assemblies	Participation, attendance, and motivation to attend the assemblies and, therefore, involvement in decision-making processes	In forest rural communities, attendance to assemblies is mandatory in accordance with the national legislation. However, the attendance indicator alone is insufficient to assess willingness to participate in decision-making, so a sustainable forestry project may be jeopardized (Brenner, 2018).				
Formal and informal rules or institutions	Access to programs and incentives	Participation in previous programs or incentives to acquire the digital infrastructure and human resources to gain access to different public policy incentives. Policies for poverty reduction through employment opportunities, availability and access to resources (including land and natural resources and means of production), and equity in the provision of public services (Andréassian, 2004).	Making a better decision that favors the wellbeing of the community and the forest is facilitated when there are a variety of projects, programs, or incentives. At the same time, ignorance feeds prejudices and lack of confidence in public policy programs (Van Strien et al., 2019).				
	Programs or funds received	Incentives and programs for sustainable forest management related to public policy (Feisntein and Ballart, 2016).	Communities that have participated in previous programs with positive effects on the community have higher possibilities to transition toward more sustainable management practices and forms (Andréassian, 2004).				

(Continued)

TABLE 3 (Continued)

Social or ecological processes to evaluate	Measurement indicators	Indicator definition and delimitation	Evaluation example	Data from:			
				Interviews		Surveys	Literature
				To community	External		
	Access to decision-making in resource utilization	Governance system that allows decision-making on the type of utilization and economic activities of the community (Andréassian, 2004).	Communities ruled by polycentric governance have achieved greater success in the transition to more sustainable management programs (Ostrom and Mc Ginhis, 2014).				
	Impact of forest harvesting	Set of impacts of regeneration techniques, clearing techniques, wood harvesting techniques. Impact of practices at the landscape level: Connectivity between habitats, network of conservation areas, habitat protection in upper-basin areas, protection of riparian ecosystems (Turner and Robbins, 2008).	The impacts of these three harvesting techniques have distinct effects on different plots; in turn, the magnitude of the impacts also depends on the biotic and abiotic factors of the ecosystem. As a consequence, the provision of ecological functions is affected (Oyarzún et al., 2005).				
	Territorial distribution	Areas of the territory dedicated to economic activities (conservation areas, crop land, management plan) (Castillo-Argüero et al., 2014).	Conservation and utilization areas largely define the capabilities of new utilization forms. Conservation areas or agricultural land (Clark et al., 2003; Jansen, 2013).				
	Intensity of forest harvesting	Hectares of forest harvested annually, cubic meters of wood harvested or processed within communities (Antoni et al., 2019).	The intensity of utilization is the result of forest management techniques, public policy, and market pressures (Castillo-Argüero et al., 2014).				
	Structure, composition, and diversity of plant communities	Biodiversity, understood as an element of ecosystems that supports the diversification of ecosystem service provisioning (diversity of arboreal, herbaceous, and microbial communities), and indices such as structural complexity that functions proxies of ecosystem services (Gathany and Burke, 2011).	The diversity of commercial species within plantations is a consequence of the management plan, understood from the richness of forest trees, herbs, fungi, and bacteria (Berkes, 2007).				
	Wood supply	Estimated from Net Primary Productivity. It also includes wood production and sales (Haines-Young and Potschin, 2009; Ordoñez Benjamín José Antonio, 2001).	The volume of wood harvest extracted annually from the ejido and the regional markets in which it is distributed shall be understood as the intersection between the provision and distribution of forest resources and their utilization by the local stakeholders within the ejido (Astier et al., 2012; García-Barrios et al., 2015; Sarukhán and Dirzo, 2013).				
	Climate regulation	It refers to reservoirs and fluxes between Carbon stores in soil, climate regulation, temperature, and precipitation, and the local impacts caused by forest mass removal (Chen et al., 2016; Van Noordwijk et al., 2020).	Carbon concentration, flow, and interaction between different carbon stores; carbon cycle throughout crop plantations (Stuart-Haëntjens, 2015).				

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TABLE 3 (Continued)

Social or ecological processes to evaluate	Measurement indicators	Indicator definition and delimitation	Evaluation example	Data from:			
				Interviews		Surveys	Literature
				To community	External		
	Recreation services	Services provided by forest ecosystems related to knowledge or recreational activities (ecotourism and craft making, among others) (Balvanera, 2012).	Ecotourism, craft making, food markets, mushroom trade, forest management, or hiking activities (Oyarzún et al., 2005; Santibañez-Andrade et al., 2015)				
	Soil fertility	Index related to total nutrients, available nutrients, and microbial activity (Bünemann et al., 2018).	Available nutrients largely reflect soil fertility and the likelihood of regeneration of a new forest mass. The intensity, frequency, and technology used in forestry practices can significantly reduce soil nutrient stores and impact physical properties, which affect fertility (Wardle and Jonsson, 2014).				

m^3r. The information gathered from interviews and workshops shows that an increasingly greater wood extraction over the years does not necessarily translate into a higher income for the communities. The forest SES of central Mexico are no exception to these commercial dynamics that can promote the use of more intensive forest harvesting methods or cover a greater exploited area to ensure the production of wood for export, disregarding other forest resources. Therefore, they have the potential to transform the dynamics of forest SES (Malhi et al., 2014). For example, wood harvesting, clearing, or plantation regeneration practices may affect the size of the area harvested per year, the number of regenerated seedlings, or the presence of native tree species. For the temperate forests of central Mexico, the main markets have focused on roundwood and fuelwood, but newly emerged markets include tourist services and incipient gastronomic markets such as mushrooms. Although short-term changes in the market affect decision-making, long-term changes in demand have a greater influence on investments in forestry and the forest industry. As a result, the current globalization makes ecological dynamics and the supply of nature contributions vulnerable to large-scale processes. Additional issues in the economic forest sector include land tenure insecurity, inadequate organization of ejidos and communities as commercial forest production units, localized exploitation of the forest resource, foreign trade in forest products with a negative balance of 12,000 million Mexican pesos per year in the private sector, plus an international competitiveness crisis. In addition, there is an inadequate institutional and legal framework to promote sustainable forest production, resulting in high transaction costs and lack of administrative continuity and public policies. Further, this becomes increasingly important considering the observed increase in natural disturbances (Senf and Seidl, 2021), which have the potential to disrupt markets, especially in the case of large even-aged forests.

3.3 How adaptation strategies of managed forests are currently implemented?

The capacity for adaptation in forest SES is closely tied to governance structures, community participation, and sustainable forest management practices (Table 3). Adaptive capacity is evident where communities construct, agree upon, and modify rules to manage forest resources effectively, as seen in systems fostering trust, reciprocity, and collaboration. Trust in local and external institutions is crucial for adopting new forest management strategies; without them, transitions to sustainable practices face significant barriers. Conflict resolution mechanisms and community decision-making processes also play pivotal roles in empowering disadvantaged groups and ensuring inclusive participation. For example, involving women and youth in forest management fosters diverse approaches, while knowledge of sustainable harvesting practices promotes transitions to resilience-focused strategies. Furthermore, participation in programs and incentives facilitates better decision-making, enabling communities to align forest utilization with ecological and socioeconomic goals. However, challenges remain, such as inadequate trust in external proposals and limited access to programs. Adaptive capacity is also shaped by forest management impacts, including land-use distribution, harvesting intensity, and biodiversity conservation. Practices that maintain habitat connectivity, protect critical areas, and prioritize ecosystem services like carbon storage and soil fertility strengthen resilience. These findings underscore the importance of fostering inclusive governance, integrating local knowledge, and adopting adaptive forest management practices to enhance the SES capacity to respond to change effectively.

Our results indicate that adaptation strategies remain inconsistently applied, highlighting the need for more comprehensive and targeted measures. The findings emphasize that SES resilience in forested areas depends not only on addressing the ecological dynamics of forests but also on integrating governance, social, and economic factors. Forest governance, as a decision-making component, plays a pivotal role in determining the success of adaptation measures. Contributions of nature, being inherently anthropocentric, align closely with social and economic dimensions while influencing ecological outcomes. Despite some progress, the absence of widespread implementation of adaptation strategies limits the system's ability to resist and recover from disturbances. Intensive forest management, while focused on maximizing short-term outputs, often undermines the provision of key ecosystem services, particularly regulatory and supporting contributions. Semi-intensive management demonstrates greater potential for fostering resilience, though it still requires improvements in the application of adaptation strategies, particularly in non-material contributions.

Three critical strategies were identified to enhance resilience in managed forests: (1) Anticipating unwanted shifts, establishing regular monitoring systems for forest health using advanced technologies such as satellite imagery, drones, and sensors. Developing predictive models to identify potential regime shifts and guide proactive management actions. (2) Maintaining diversity and feedback interactions. Promoting sustainable forestry practices, including selective cutting to preserve species diversity and avoid monoculture. Encouraging natural regeneration with native species and supporting mixed-species plantations to enhance ecological functions. (3) Strengthening resilience: implementing practices that improve resistance to natural disturbances, such as age and species diversification; and enhancing local knowledge and fostering community-based management to support adaptive capacities and equitable governance structures. Climate change and increasing environmental pressures demand a shift toward adaptive and sustainable practices. Public policies need to focus on supporting long-term resilience by integrating local knowledge, promoting polycentric governance, and addressing socio-economic vulnerabilities. For example, transitioning toward mixed plantations and diversifying economic activities within forest-dependent communities can mitigate risks associated with climate change and enhance ecosystem stability.

4 Discussion

4.1 Social-ecological components and interactions dynamics

The conceptual model of social-ecological resilience for forest systems in central Mexico illustrates the complex and dynamic interactions between multiple factors influencing forest management. This interactive dynamic highlight that resilience cannot be attributed to a one-way, direct relationship between ecosystems and natural resources, but instead is driven by feedback loops where each component—whether it is vegetation, forest area, or socio-economic drivers—mutually influences the others. The interaction between regional and local governance levels is vital to facilitating forest resilience, as both national policies and local governance structures influence forest management practices. While, at the ejido level, decision-making processes are designed to be democratic and participatory, involving landowners and external stakeholders like forestry technicians. However, challenges remain in fostering inclusive participation, particularly from women and youth, who play an increasingly critical role in driving change. Effective polycentric governance that decentralizes decision-making and encourages community participation can promote forest resilience by aligning local knowledge and practices with broader policy frameworks.

In Mexico, ecosystem conservation goals remain inconsistent with production, growth, and economic development goals, even as regards public forest policies. If no policy actions are taken, SSE of Mexican forest will struggle to provide the contributions of nature demanded in the future. In our case study, socio-economic pressures, particularly liberalized markets and unrestricted migration, severely impact the system's ability to supply nature contributions in the long term. Globalization often operates as a top-down regulatory process that disregards local conditions and knowledge, creating direct constraints on farmers' management practices and, consequently, on contributions of nature provision. An example of this dynamic in Mexico is the management of community forests in Oaxaca. While these forests are globally recognized for their biodiversity and carbon storage, the expansion of liberalized markets and migration has led to reduced local labor and traditional knowledge needed for sustainable forest management (Jurjonas and Seekamp, 2019).

Public policy in forestry matters seeks to address specific social issues such as poverty and marginalization of forest rural communities (Baud et al., 2011; Merino-Pérez and Segura-Warnholtz, 2005). It has committed to sustained maintenance over time only based on the high productivity conditions of Mexican soils. For example, the implementation of new policies on wood harvest intensification or access to certifications has effects on a national scale. SES with certifications in sustainable forest management show greater post-harvest soil recovery and diversity of tree species. Certification of 2.46 million ha collective property has been fostered by government programs to support community forest management, i.e., the Forest Development Program and the Forest Resources Conservation and Management Project launched in 1997 by the then Secretariat of the Environment, Natural Resources, and Fisheries, later transferred to CONAFOR in 2001. The conservation of forests, their sustainable use, and the permanence of forest rural communities largely depend on the strengths of local institutions such as social capital, which can be strengthened through incentives to the community forestry sector. This is ineffectiveness of decentralization of policies that support the participation of local communities in forest management because decentralization is directly related to the power and autonomy within an organization. Another example is found in the General Law on Sustainable Forestry Development 2018, where Sustainable Forest Development is defined as a "process suitable for evaluation and measurement through environmental, forestry, economic, and social criteria and variables that tends to achieve optimal and sustained productivity of forest resources." Institutions have not supported the implementation of new policies on wood harvesting intensification or access to certifications that influence management practices within forests.

Another such process is the incentives to acquire market-driven sustainable forest development certifications; these certifications directly impact forest management practices in plantations and the social organization of communities too (Walker et al., 2002). Sustainable certifications involve the conservation of unharvested areas that allow soil recharge and prevent the erosion of soils already harvested historically, forest policy in Mexico has aimed to address socioeconomic issues within rural forest communities, emphasizing sustainable management and certification-driven approaches. However, the new policies, focusing on forest restoration since 2018, alter incentives surrounding contributions of nature such as timber production, in favor of ecosystem conservation. Therefore, considering recent and rapid changes in forest policies, it is crucial to examine how these updated frameworks fit within the existing forest management model and, importantly, how the model adapts to these shifts. For example, despite efforts to decentralize management and promote community-based forest management, the disconnect between ecosystem conservation and economic goals remains evident. The results indicate that intensive management methods do not support the sustainability of key ecosystem services. For example, intensive management limits the provision of several material, regulatory, and non-material contributions, while semi-intensive management supports a broader range of contributions, albeit with certain limitations. This distinction reveals the need for adaptive forest management strategies that prioritize biodiversity conservation, sustainable resource use, and community wellbeing. Semi-intensive management, which maintains ecological functions and promotes natural regeneration, is more favorable for enhancing the resilience of forest ecosystems in the face of disturbances.

The pressures exerted by global markets and climate change are significant threats to forest ecosystem resilience. Globalization and market demands have led to an intensification of wood production, often at the cost of other forest resources. This trend is exacerbated by inadequate institutional support for sustainable forest management and economic pressures related to timber exports. The results suggest that forest management practices driven by short-term economic gains may undermine the long-term resilience of ecosystems. Moreover, climate change impacts, including changes in precipitation and temperature patterns, are already altering the habitat suitability for species, disrupting forest dynamics, and increasing the frequency and intensity of disturbances such as forest fires and pest outbreaks. These findings highlight the urgent need for a comprehensive approach to forest management that integrates climate change adaptation strategies, enhances the adaptive capacity of forest systems, and ensures the continued provision of ecosystem services. In recent years, forest harvesting in Mexico has been carried out through community forest management, which seeks to obtain forest services and resources that sustain better living conditions in local populations. Management can promote changes that directly impact the functioning of the ecosystem through the individual and collective management actions organized and implemented, for example, modifying spatial distribution, structure, composition and diversity of plant communities. Public policy programs have strongly influenced forest management. For example, the 2001–2025 Strategic Forestry Program aims to promote sustainable forest management, yet the conifer and broadleaved forest declined from 67,856 thousand ha in 2000 to 66,040 thousand ha in 2015, mainly due to grazing, fires, and changes of land use (CONAFOR, 2017).

Public policies concerning forest harvesting have opted for an intensification of wood harvesting, which has had negative impacts on attributes that favor resilience in forests, such as a reduction in biodiversity and forest connectivity (Kolb and Galicia, 2018). This loss of biodiversity of tree species and other flora and fauna translates into the loss of redundancy of biological communities (Guerra-De la Cruz and Galicia, 2017). Monoculture has markedly reduced species richness and diversity of forest plantations toward commercial species such as *Pinus patula*, *P. moctezumae*, *P. pseudostrobus*, and *P. teocote*. This has led to the displacement of native pine and oak species, which in turn is causing a change in the tree communities (Balvanera and Cotler, 2009). Selective cuttings have changed the structural parameters, composition, and regeneration of forests, influencing the diversity of the communities involved. Natural regeneration occurs only rarely in areas managed under the two forest systems; for example, from 1962 to 1985, more than 36 million seedlings were planted in an industrial 42,700 ha forest unit in central Mexico. Currently, most plantations are mono-specific and show a predominance of one or two age groups (CONAFOR, 2020). The aim is for productivity at minimal cost, with little regard for contributions of nature, which are neither evaluated nor incorporated into economic assessments; this limits the carbon capture and storage in Mexico. According to the 2016 Forest Production Statistical Yearbook, in 2007 the harvest in Mexico was 7 million cubic meters wood in roundwood (m3r), but in 2016 it had decreased to 6.7 million m3r (CONAFOR, 2017). Historically, timber production has exploited pine and oak forests. Pine production has contributed >80% of the value since 2011.

4.2 Enhancing social-ecological resilience in Mexican forests

There are important mechanisms in governance or the process of decision-making that are key for promoting resilience mechanisms in social and ecological subsystems. Polycentric governance brings resilience to forest SES; it must resolve conflicts, build institutions and rules to boost change through the decentralization of decision-making and preserve key social-ecological elements in the face of disturbance and change. In the forest rural communities of central Mexico, governance is at two levels: the regional or national level delineates forest harvesting guidelines and is formed from federal government organizations (SEMARNAT, CONAFOR, and PROFEPA); and the local or ejido level which involves the political representation of landowners. The interdependence of national and local governance is essential, provided this does not lead to the loss of autonomy of decision-making bodies; networks within and outside the community can significantly strengthen its capacity to restrict disturbance, whereas strong social links within the community are favorable for the self-organization of SES. The ejidal assembly is the main authority at the ejido level, it is composed of internal actors (landowners) and external actors (forest technicians) and is guided by the practices of the local communities, for example to determine harvesting methods and monitor forest harvesting in accordance with current regulations, respectively. Although decision-making within the ejidal assembly is intended as a democratic, participatory, and horizontal process, several challenges remain, such as the inclusion of women and young people who have been important change factors in forest management. Also, assemblies usually meet once a month, but not always with the participation of all assembly members. An advance toward polycentric governance in the forest rural communities of central Mexico will decentralize power over natural resources and enable collective action by social institutions that, being located on site, understand the root cause of conflicts. In practice, this involves considering a diverse range of factors, from biological diversity and forest structure to the needs and knowledge of local communities (Saxena et al., 2016; Vázquez-González et al., 2021). Community participation and effective governance are woven into the fabric of forest resilience. Involving local communities in decision-making and recognizing their traditional knowledge not only fosters equity but also strengthens the connection between people and mutually dependent forests (Falk et al., 2022).

The social-ecological forest systems of Mexico are likely to be modified by changes in wood markets and the intensification of wood production through public policies with economic subsidies and loans to all those interested in participating in the production or export process; while other forms of management (ecotourism, wood processing, non-timber forest products) will become almost unviable (Villaseñor et al., 2008). If market globalization is prioritized, policies will focus exclusively on timber harvesting because the goals of ecosystem conservation and adaptive capacity generation set for the SES of Mexico are still inconsistent with the production, growth, and economic development objectives. For instance, the 2018 General Law establishes Sustainable Forest Development as a "process suitable for evaluation and measurement through environmental, forestry, economic, and social criteria and variables that tends to achieve optimal and sustained productivity of forest resources." In fact, in 2010 some 10 million m^3 of wood was being extracted annually at the national level, but by 2024 this figure is projected to be 24 million m^3 annually (CONAFOR, 2020). Therefore, it is essential that Mexico's sustainable forest development policies integrate the principles suggested for strengthening adaptive capacity to ensure the continued maintenance of wood production in scenarios of temperature change, changes in markets, or changes in the socio-demographic conditions of forest rural communities (Cubbage et al., 2015).

In the SES of central Mexico, which face the intensification of timber harvesting and, consequently, a nested effect that reduces the supply of contributions of nature, the only attributes capable of coping with changes in the dynamics of these systems are the conservation of biodiversity and the maintenance of slow variables (soil fertility and coarse wood residues). Therefore, the design and implementation of forest management plans should switch toward practices that contribute to this capacity, such as mixed forest plantations (Walker et al., 2002). Mixed plantations can improve water, light, and nutrient use. Under this approach, it is imperative to maintain ecological functions in forest plantations as similar as possible to those of non-managed forests (Lindenmayer et al., 2016). It is also essential to enhance natural regeneration with native species to promote diversity and successful establishment. Establishment of nurseries to enhance plant quality is crucial in the processes that confer resistance to native ecosystems (Bonnesoeur et al., 2019). In addition, the development of locally owned sources of improved germplasm and technologies to produce good-quality plants is imperative for plantations of native species with high production potential. If there is no transition to silvicultural management practices that contribute to this capability, the buffer capacity will be exceeded in the long term. For example, genetic improvement in Mexico of species such *Pinus patula*, and *P. pseudostrobus* is still in the early stages, and at least a decade is required before the first results are attained, whereas some countries (e.g., South Africa) have already developed genetic improvement programs for *P. patula* (Bellón et al., 2009). Similarly, the technologies for production of good-quality plants in nurseries for plantation and reforestation programs still have flaws that should be addressed through specific research at the local level. This situation contrasts sharply with the great diversity of tree species that prosper in the forests of Mexico, with more than 150 species of oaks and more than 47 species of pine, not counting the tropical species. An alternative approach to counter the effects of climate change is to select species tolerant to water stress and pests, particularly using mixed forest plantations or species corridors (Galicia et al., 2015; Lindenmayer et al., 2016). It is essential to maintain species diversity if forests are to be transformed into more sustainable SESs with a wide range of economic activities. In specific cases, targeted post-disturbance actions such as supporting genetic variability and provenance selection in assisted migration may promote forest resilience (Park and Rodgers, 2023).

Forest management, depending on its structure and dynamics, can fit within any of the social-ecological resilience categories. If there is no adaptive strategy to cope with the effects of the major hazards facing these ecosystems, forests will see reduced opportunities for transition toward sustainable use. Forest resilience is closely related to the provision and maintenance of contributions of nature, as the ability of an ecosystem to resist and recover from disturbances is intrinsically linked to its ability to continue to provide these contributions of nature effectively. For example, in a temperate forest, wood production and water regulation are closely tied to the forest's resilience to disturbances like storms or wildfires. A resilient forest, with diverse species and healthy soil, can recover from such disturbances and continue to provide timber and regulate the water cycle, ensuring these contributions of nature are available for local communities over time (Falk et al., 2022). The simultaneous study of different stressors and shocks allows a better understanding of how systems react to several disturbances at the same time, and consequently a measurement of general resilience. For example, in a temperate forest, studying the simultaneous impacts of wildfires, drought, and invasive species allows for a better understanding of how the ecosystem responds to multiple disturbances at once. By assessing how these stressors affect biodiversity, water quality, and wood production together, we can measure the forest's general resilience (Preiser et al., 2018). This approach helps identify vulnerabilities and adaptive capacities, ensuring the forest can continue providing essential contributions of nature even under compounded pressures. The optimization of system elements to a specific goal causes specific resilience but general resilience might decrease. In addition, climate change demands a response articulated between ecological and social elements, including mixed plantations or the use of other commercial species within the forest industry. On the other hand, changing climate patterns and natural disturbances require forest management practices to be agile and responsive (Konstantinov, 2011; Rehfeldt et al., 2014). The implementation of adaptive silviculture techniques, introduction of resilient species and constant monitoring are key facets of strengthening the capacity of forests to cope with changing conditions. Involving local communities in decision-making and recognizing their traditional knowledge not only fosters equity but also strengthens the connection between people and mutually dependent forests (Smit and Wandel, 2006; Thornton and Comberti, 2017). Measuring resilience is difficult, we identify underlying past forest collapses—and the thresholds that were exceeded—is a critical first step to applying a resilience approach (von Stackelberg, 2018). For example, thinning, the promotion of tree species diversity and the cessation of active forest management are in the focus of scientific and policy discussions to enhance the resistance of forests in Europe in relation to droughts (Moreau et al., 2022; Nagel et al., 2023).

5 Conclusion

Our analysis highlights the complex relationship between forest management practices and SES resilience, especially in the context of climate change and public policy. This theoretical foundation helps us frame our analysis within the broader scientific discourse and guides our exploration of practical strategies to improve resilience in the face of current and future challenges. Through a comprehensive review of scientific literature and the collection of empirical data including household surveys, key informant interviews, and focus group discussions, we develop a conceptual framework that depicts cause-effect relationships among these components and describes how disturbances, such as climate change and policy can affect the dynamic nature of resilience. These findings underscore the importance of integrating governance, social, economic, and ecological components into forest management to enhance resilience in the face of multiple stressors and future climate impacts. Therefore, our conceptual model provides a valuable tool for guiding decision-making in the management and conservation of these ecosystems. For example, the development of public policies toward the sustainability of harvesting systems in the forests of central Mexico requires an understanding of social ecological dynamics and the conversion of these concepts into practical support for the resilience capabilities of these social-ecological systems. This could reduce the risk of effects on vulnerable or marginalized people, as well as clarifying the societal and systemic implications of a specific transformation. Also, our conceptual framework describes how disturbances, such as selective logging and forest fires, can affect the stability and function of temperate forests. Through an integrated, multidisciplinary approach, we hope to contribute to the development of effective strategies to ensure long-term health and sustainability of temperate forests in the context of global environmental change. It is our hope that this initial work will serve as a basis for future research and action to strengthen the capacity of our forest systems to meet the challenges of the present and future.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical approval was not required for the studies involving humans because Ethical approval was not required for this study as we only conducted interviews with ejidatarios to understand the history of the ejido and the objectives of forest management. The interviews focused on gathering historical and contextual information, which does not fall under the scope of research requiring ethical approval. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

LS-M: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Visualization, Writing – original draft. LG: Conceptualization, Funding acquisition, Investigation, Validation, Writing – review & editing. SÁ-F: Conceptualization, Investigation, Methodology, Supervision, Validation, Visualization, Writing – review & editing. TM: Formal analysis, Investigation, Project administration, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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