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Sustainable Community Forest Management in Mexico: An Integrated Model of Three Socio-ecological Frameworks

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Abstract

The sustainability of management practices in forest ecosystems should provide ecosystem services and maintain the livelihoods that largely depend on the benefits directly derived from forests; but this goal requires various theoretical and analytical approaches. This research aims to develop a conceptual model for sustainable forest management based on the integration of three conceptual frameworks founded on the society–ecosystem interaction: socio-ecological systems, sustainable forest management, and ecosystem services. The results offer a methodological, analytical, organizational, and operational route to integrate a scientific model at the material, causal, and dynamic levels, considering theoretical and empirical information; it uses grounded theory methodology to select the interactions between variables and socio-ecological dynamics of forest ecosystems under community management. For example, it integrates social components (local knowledge, governance, and social organization) and ecological components (diversity and composition of plant species, carbon pools, and nutrient dynamics) to understand their interactions through management practices and the magnitude of the ecosystem services provided according to the local contexts. We illustrate this process by analyzing the influence of governance, decision-making, resource use, and management practices on forest management and ecosystem services; this exemplifies the factors, interactions, and effects on socio-ecological systems based on experience in forest communities. These integrated frameworks provide steps through which our understanding of specific socio-ecological approaches produces better outcomes for sustainable forest management, preserves ecosystems services and benefits livelihoods in Mexican temperate forests.

Keywords Ecosystem services · Governance · Local knowledge · Social organization · Socio-ecological systems · Sustainable forest management

Introduction

The implementation of a model of forest socio-ecological systems (SES) could aim to achieve sustainability through the creation of self-management practices that allows local inhabitants to make good use of forests through incentives to encourage management. The goal of forest sustainability is to ensure continuous production of timber and non-timber products, support the supply of multiple ecosystem services; or to an increase in forestry skills that may indirectly help to support the livelihoods of local communities (Jabareen 2009; Messier et al. 2013; Pope et al. 2017). Despite and given these complexities, there is an urgent need to strengthen the understanding of how sustainability goals can be achieved through the design and implementation of forest policies, government investments, local forest management and social stakeholders, and institutional projects. Over the past decade, studies on sustainable forest management have adopted a SES perspective (Messier et al. 2013; Williams and Brown 2016; Sabatini et al. 2015) to explore the relationships and dynamics between social stakeholders (individuals and communities) and natural and managed ecosystems (Zurlini et al. 2008; Turner et al. 2016). Investigation of social actions that contribute to sustainable forest management has entailed various theoretical approaches including socio-ecosystems (Collins et al.

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2011; Herrero-Jáuregui et al. 2018; Colding and Barthel 2019), sustainable forest management (Varma et al. 2000; Gough et al. 2008; Mori et al. 2017), and ecosystem services (ES) (Van Oudenhoven et al. 2012; Reyers et al. 2013; Truchy et al. 2015; Mori et al. 2017; La Notte et al. 2017). There are studies that analyze these approaches through a binary methodology (Herrero-Jáuregui et al. 2018; De Vos et al. 2019; Coldingand Barthel 2019); however, the SES aspect has been used to explore forest production from the perspective of complex systems (Messier et al. 2013; Wallace et al. 2018) through adaptive management (Saxe et al. 2001; Galicia et al. 2015; Pérez-Orellana et al. 2020) and the maintenance of ecological functions in complex forest ecosystems (Lindenmayer et al. 2016; Wallace et al. 2018). These approaches have often been oriented towards project design and implementation or have focused on sub-sections of the wood provision without adequate attention to the bigger-picture linkages that are frequently needed for consideration by policymakers and social stakeholders. Despite these theoretical and empirical advances, only a few studies have integrated the SES and ES (Perevotchikova 2020; Rodríguez-Robayo et al. 2020), but without reference to sustainable forest management (SFM) and analytical frameworks to examine the interactions between forest management practices and the ecosystem services. Conceptual frameworks provide not only a structure that guides research and analysis but also the basis for positioning, comparing, and reflecting on a set of practices within the scope of possibilities defined by these frameworks. We support this theoretical approach, as a strong contribution to the transition toward more sustainable forest SES because it is sustained on the grounded theory (Strauss and Corbin 1994; Charmaz 2001) approach developed from systematic analysis of empirical data that guide the qualitative data collection from local actors, theoretical model construction and data analysis.

This work uses forest management in central Mexico as a model to gain a theoretical understanding of the interaction of management practices with ecosystem functions and services, on one hand, and with governance and social organization, on the other. This research also documents the sustainability issues unique to shared resources. The temperate forest socio-ecosystems of central Mexico are home to 50 pine (*Pinus* spp.) and 140 oak (*Quercus* spp.) species, accounting for ~50 and ~30% of the world total for each genus, respectively (Valencia 2004). Seventy percent of forest land is owned by local administrative units called "*ejidos*" and by local communities (Madrid et al. 2009). This study seeks to go beyond social studies in forest ecosystems, which have focused on understanding governance (Ruppert and Antinori 2008), community organization (Bray et al. 2007), and forestry practices based on social cooperation (Antinori and Rausser 2007; Taylor 2012). However, there are no studies associating social management practices with the effects of interactions between social and ecological subsystems over time. This aspect is worth reviewing, as forest exploitation in Mexico faces various issues, such as a timber production deficit for the domestic market, the protection of biological diversity and the supply of multiple ecosystem services, and the economic and social well-being of the local communities (Thompson and Christophersen 2008; Galicia and Zarco-Arista 2014; Merino and Martínez 2014).

Given the ecological and social relevance of forest management in Mexico based on empirical knowledge of forest communities in central Mexico, we developed a model to analyze sustainable forest management at the "*ejido*" level; its purpose was to understand the multiple factors and forces that define socio-environmental issues and processes (Parsons 2013). To our knowledge, in Mexico no framework exists that conceptualizes the key relationships among socio-ecological systems, sustainable forest management, governance, local knowledge, social organization, and ecosystem services informing policymakers concerned with improving forest multipurpose management. Therefore, this research addresses the following topics: (1) the benefits of building a conceptual framework integrated by SES, SFM, and ES, and (2) socio-ecological interactions that underpin the sustainability of managed forest socio-ecosystems in the central region of Mexico. We first identify and describe each of the three analytical frameworks and describe the selection and integration process for the variables considered. We then propose a model that allows the analysis of socio-ecological interactions in specific spatial contexts and their implications for the sustainability of these practices in community-based forest management. This conceptual framework evidences the challenges faced by decision-makers and forest communities in implementing various management practices. The study emphasizes the need for the sustainable management of SES.

Methods

Region Analyzed

In Mexico, temperate forest ecosystems are natural assets associated with a set of strategic services at the national level: maintenance of high biological diversity; soil stabilization; regulation of the hydrological cycle and climate; and water and carbon sequestration (Galicia and Zarco-Arista 2014). In addition, these forests are the source of subsistence products for many local communities—a clear example of the relationship between the welfare of human communities, the economy, and forest resources (Bray et al. 2007). Of the

26 million rural inhabitants of Mexico, 17.7 million live in forest land, where 15,584 *ejidos* and communities with more than 200 forest hectares are located (Chapela and Merino 2019). We selected the forest community as the socio-ecological unit for analyzing forest resource management influenced by national forest policies and various forms of collective actions at the local level. These collective actions have been key drivers in establishing rules and techniques for silviculture and the development of the local communities. The *ejido* is also the institutional platform for the governance of shared resources and a highly appropriate territorial unit of analysis (Monroy-Sais et al. 2016).

The application of strategies and actions technically and scientifically supported in forest *ejidos* and communities is essential if sustainable forest management is to be achieved. It favors the conservation of natural assets, biodiversity, and the maintenance of the structure, functioning, and stability of the ecosystem component of these socio-ecosystems. The approach to forest production processes has traditionally been limited to ensuring timber target yields through various forestry practices in place in Mexico, with minimal or no attention to preserving the characteristics of soil, biodiversity, and natural regeneration (Galicia and Zarco-Arista 2014). In addition, management programs in *ejidos* and forest communities have not been adapted to the current requirements of socio-ecosystem sustainability, as their approach and practice focuses on timber productivity, without incorporating the ES framework that allows an understanding of the effects of forest management on ecosystems. The present study considers sustainable forest management as an integration of social, economic, and environmental elements, and it uses forest *ejidos*/communities as units of analysis. Systematic analysis of empirical data considered the interactions between the various components of socio-ecological systems at the local level; this should lead to the proposal of alternatives for their sustainable use. To develop an original analytical framework of the forest socio-ecological systems, we reviewed the literature and conceptual frameworks to find those that illustrated aspects of the relationships and feedbacks among governance, forest sustainability, and ecosystem services. This led to the development of an analytical framework of forestry that addresses the characteristics of and interactions between the social and ecological functioning of forestry systems and the socio-political contexts in which forest communities are embedded.

Integration of Conceptual Frameworks

The study of SES in managed forest ecosystems requires multiple methodologies and approaches to achieve a systemic understanding of the interactions and dynamics of socio-ecosystems (Ostrom 2009; Carpenter et al. 2012; Levin et al. 2013), as well as the construction of new models and the integration of analytical frameworks (De Vos et al. 2019). Several qualitative methods were used for constructing the analytical model of socio-ecosystems (referred to in Oh and Oh 2011), as described below. In particular, the grounded theory method allows codified steps in analyzing qualitative data. Their distinctive features include: (a) simultaneous data collection and analysis, (b) reliance on comparative methods, (c) early development of categories, (d) intermediate analytic writing between coding data and writing the first draft, (e) sampling for developing ideas, (f) delay of the literature review, and (g) a thrust toward developing theory (Charmaz 2001). An assessment framework is developed based on the conceptualization of integration emerging from a literature review, along with in-depth interviews, participant observation, and document review regarding forest management in Mexico.

In the first phase, the categories and variables of each analytical framework were identified to analyze the sustainability of management practices in forest socio-ecosystems and the interactions developed to achieve local ecosystem management at different spatial scales (De Vos et al. 2019). The objective was to visualize and explain the effects of interactions between managed social and ecological subsystems. To this end, we conducted a literature review and a comprehensive analysis of the scientific information and gray literature published, aiming to combine the SES, SFM, and ES frameworks. Afterward, the variables that make up the three frameworks were analyzed, and the suitability and compatibility of the theoretical approaches with the local contexts were evaluated to assess sustainability in managed forest socio-ecosystems at the *ejido* level.

In the second phase, the variables of each analytical framework were operationalized to generate hypothetical relationships between social and ecological domains of each analytical framework based on published articles and secondary information (Tenza et al. 2017; Cole et al. 2019; De Vos et al. 2019). This phase determined the functional relationships and correspondence between the variables in each framework, considering the empirical reference in their construction (Bulmer 1984; Strauss and Corbin 1994; Charmaz 2001; McGinnis 2011; Cole et al. 2019). To systematize the information and its analysis, matrices were constructed for each analytical framework, including categories, variables, and observables. The operationalization of the SES framework considered specific examples reported in other studies in which variables and subvariables (first-, second-, and third-level) are broken down in detail (Ostrom 2009; McGinnis 2011; Leslie et al. 2015; Cole et al. 2019; Perevotchikova 2020). The first-level variables proposed by Ostrom (2009) that were adapted were: Resource System (RS) representing forest ecosystems that exploit timber

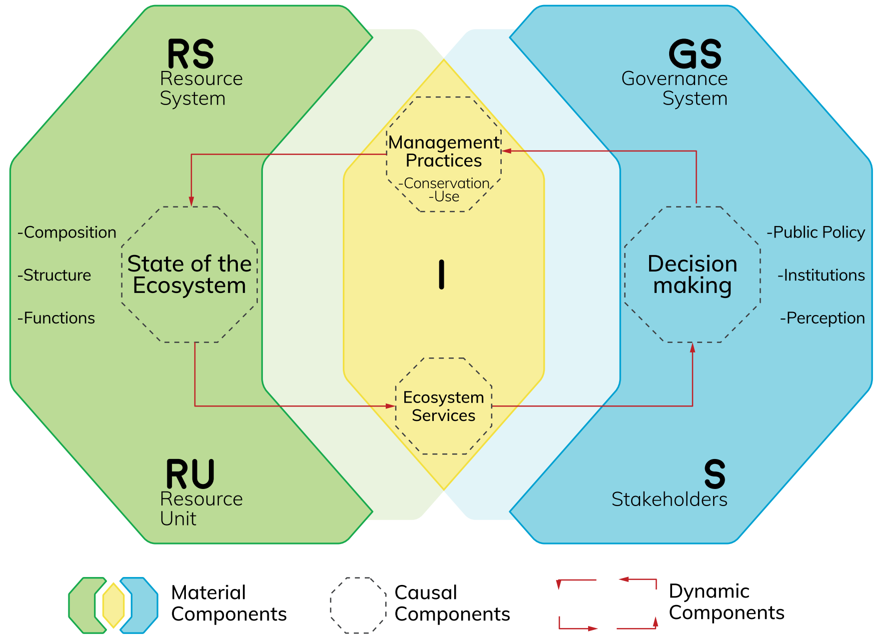

Fig. 1 Interaction model of managed forest socio-ecological systems in central Mexico. Green and blue octagons encompass the *material components* of the model: green, the ecological subsystem with RS and RU; blue, the social subsystem comprising S and GS. The *interactions between causal components*, i.e., those that explain the functioning of the model, are represented by decision-making, management practices, ecosystem status, and ecosystem services provided. The material and causal components interact dynamically (dotted octagons and arrows)

species; Resource Unit (RU) including timber trees; Governance System (GS) consisting of the *ejido* assembly (the highest authority within the *ejido*); and the Stakeholders (S) including the forest producers involved (Sánchez-Nupan 2020). Second- and third-level variables were also included, which may vary according to the characteristics of the study areas. The same process was carried out to systematize the information from the SFM analytical framework proposed by Higman et al. (2013). This framework summarizes the Forest Stewardship Council (FSC) criteria for the certification of sustainable ecosystem management: (1) the legal and political frameworks, (2) optimal and sustained production of forest products, (3) environmental protection, and (4) the well-being of the people (Sánchez-Nupan 2020; Castro-Torres 2020). The analysis of ES was based on Nature's Contributions to People classification proposed by Díaz et al. (2018) and it considered (1) habitat creation and maintenance, (2) climate regulation, (3) soil formation, and (4) materials energy; these were associated with material, non-material, and regulatory services. Categories and indicators were established to assess whether the management techniques applied in central Mexico contribute to the sustainable use of ecosystems in forest *ejido* land (van der Sande et al. 2017; Castro-Torres 2020).

In the third phase, we identified the interactions among the variables of the analytical frameworks to integrate the model of managed socio-ecological forest systems. Integration entailed an inductive-deductive process in an interdisciplinary and qualitative analysis that combined the results of the literature review and the empirical information obtained from 19 interviews and participant observation during field visits. We interviewed 9 key external actors (government agents, forestry technicians and academics) and 10 authorities from two forest communities in central Mexico (see Sánchez-Nupan 2020), and referred to ecological information available from previous studies (Guerra-De la Cruz and Galicia 2017).

The integration of the model consisted of integrating dynamic and causal components as a representation of objects, phenomena, processes, ideas, or systems (Márquez et al. 2006; Gilbert and Boulter 2001; Oh and Oh 2011). Material components are the parts or elements of the system; dynamic components include the relationships between these parts or elements; and causal components explain the causes and functioning of the system (De Vos et al. 2019). The construction of hypothetical models on system dynamics may include qualitative and quantitative information collected through literature reviews and fieldwork in a constant reflexive procedural (Charmaz 2001; Herrero-Jáuregui et al. 2018; Tenza et al. 2017), as well as an iconic or visual representation of reality, including interpretive data that describe or predict the behavior of a socio-ecological phenomenon (Márquez et al. 2006) (Fig. 1). By combining the theoretical SES, SFM, and ES approaches constructed with empirical information, this analytical model of managed forest socio-ecosystems allows the identification, knowledge, and analysis of the processes and interactions between the various components of the social and ecological subsystems and the effects they have on sustainability (Ostrom 2007, 2009; Cobourn et al. 2018). In addition, it incorporates descriptions and analyses of the material, dynamic, and causal components, thus facilitating the understanding and interpretation of ecological interactions and processes that are interdependent with management practices that provide sustainable social, economic, and environmental benefits to the local forest communities. The framework is progressively presented in the "Results" section.

Results

Model: Components, Variables, and Interactions

The conceptual framework for sustainable community forest management represents a comprehensive effort to understand the potential and theoretical relationship of ecosystem structure and function with social, political, and economic aspects of temperate forest management in Mexico (Fig. 1). The material components of the model are framed by the social and ecological subsystems; at a second level is the governance system (GS), produced from decision-making and the interaction between internal and external stakeholders (S), who interact with each other and with the resource system (RS); their actions have positive and negative effects on resource units (RUs), i.e., forest cover and ecosystem services (Fig. 1). Our SES model helps to decipher the socio-ecological dynamics in specific contexts of temperate forests in central Mexico, allowing us to derive useful information to solve sustainability issues by comparison with a large-scale political or territorial approach and with other regions (Tenza et al. 2017). The integration of the criteria from the three approaches provides a diagnosis of the status within a forest management unit. It is thereby possible to monitor whether the set of techniques used and applied over time achieve their intended objectives (Van der Sande et al. 2017). SES models can assess sustainability by analyzing the effects of different management methods on the ecosystem (Scheffer et al. 2015; Van der Sande et al. 2017).

The causal components interaction refers to the interaction between the social and ecological subsystems through those decisions made by stakeholders that are linked to public forest policies and institutional frameworks regulating the forest management sector (Fig. 1). The integrity and relevance of these models to managers and stakeholders relies on the coproduction of knowledge between scientists and the community as well as the integration of management plan, governance, ecosystem services and ecological components of the ecosystem. These include the implementation of certain management practices (split into activities relating to the use and conservation of timber and non-timber materials) (Bray et al. 2007; Chapela and Merino 2019); and compliance with institutional frameworks and sectoral public policies—decisions related to actions that affect RSs and RUs over time, evidenced in the provision of ecosystem services. There is a complex relationship between the three model components (Table 1).

Governance and Decision-Making of Stakeholders

The main interaction between social and ecological subsystems lies in GS, including the decision-making process between internal and external stakeholders at national, regional, and local levels who set the rules governing the identity, manner, and timing of the resource management (Table 1; Fig. 1). The institutional agreements established by system stakeholders give rise to social interactions that determine management practices for resource use, conservation and markets are vital for building the tools that communities need to deal with sustainability (Fig. 1). These, in turn, trigger positive or negative results in the state of the forest ecosystem, which can be observed in the quality and supply of ecosystem services. This leads to a feedback cycle involving all the socio-ecological system components: resource system, resource unit, governance system, and stakeholders (Fig. 2).

The variables considered in the construction of the local institutional rules are existence of community rules for local governance, rules related to the use and protection of local common goods (for example, public spaces, forests, infrastructure, profit of community activities, community participation in the definition of agreements, knowledge of the rules, monitoring of their compliance, sanction of non-compliance and confidence in the fulfillment of the commitment of the peers). The analysis of the GS requires a study of the federal public forestry policy instruments currently in force and the drivers of exploitation, conservation, and social participation, thereby identifying the objectives that favor a certain type of socio-ecological interaction (Bray et al. 2007; Sánchez-Nupan 2020). In this respect, the prevailing view regarding forest management has focused on strengthening the social and economic development of populations living in many forest regions, encouraging not only the use but also the conservation of these ecosystems. These new objectives open an opportunity to develop approaches that help determine whether forests can continue supplying the quality and quantity of ecosystem services needed to preserve them in the long term while meeting the local needs.

Governance based on community participation takes place in many communities that hold community assemblies in which issues of collective interest are discussed, decisions are made, and rules are defined on the use of forests, profits from community productive initiatives, conflicts, and participation in government programs (Antonori and Rausser 2007; Thompson and Chritophersen 2008). The members of the communities who assume the different positions within the local government systems are

Table 1 Analytical variables to operational and systematic approach of the SES in a forest management system

1st level		2nd level	Criteria for sustainable forest management	Criteria of ecosystem services	Specific indicators
Resource System (RS)	RS1	Sector		Trees	Timber volume
				Firewood	Coarse woody debris
	RS2	System boundaries		Non-timber forest resources	Mushroom diversity and wild fruits
	RS3	System size			
	RS4	Built Infrastructure			
	RS5	System productivity	Optimum and sustained production of forest products		Management plans
					Regular review of the management plan
	RS6	System management			Management summaries publicly available (transparency)
					Sustained harvest Justification of the selection of the silvicultural system
	RS7	Dynamics predictability			Sustainable levels defined
	RS8	Storage characteristics			Current production of timber and non-timber forest products recorded
	RS9	Location		Geographic location	Altitude, climate
Resource Unit (RU)				Biodiversity	Timber provision Commercial species Habitat
	RU1	Growth rate		Soil	Fertility Biodiversity (fungi, bacteria) Nitrogen and phosphorus stores
	RU2	Turnover rate			
	RU3	Interactions between units	Environmental protection		Harvest rates sustainable
					Management effects monitored
					Forest protected against illegal activities
					Impact analysis/assessment
					Biodiversity conservation
					Ecological sustainability
	RU5	Economic value			
	RU6	Number of units			
	RU7	Unique features			
	RU8	Spatial and temporal distribution			
Governance System (GS)	GS1	Government organizations			
	GS2	Network structure			
	GS3	Operation rules			Compliance with laws and regulations
	GS4	Collective choice rules			Compliance with national and local regulations
	GS5	Constitutional rules	Legal and political framework		Use and Tenure Rights
	GS6	Monitoring and sanctions			Long-term land-use rights
Stakeholders (S)	S1				

Table 1 (continued)

1st level	2nd level	Criteria for sustainable forest management	Criteria of ecosystem services	Specific indicators
	Number of users and type of stakeholders			Recognition and respect for the legal rights of the local communities
S2	Socio-economic attributes of stakeholders			Commitment to forest organization and policy
S3	History of use			
S4	Localization relative to resource systems			Long-term commitment
S5	Leadership and business vision			Reinvestment of forest profits for management
S6	Regulations and social capital			

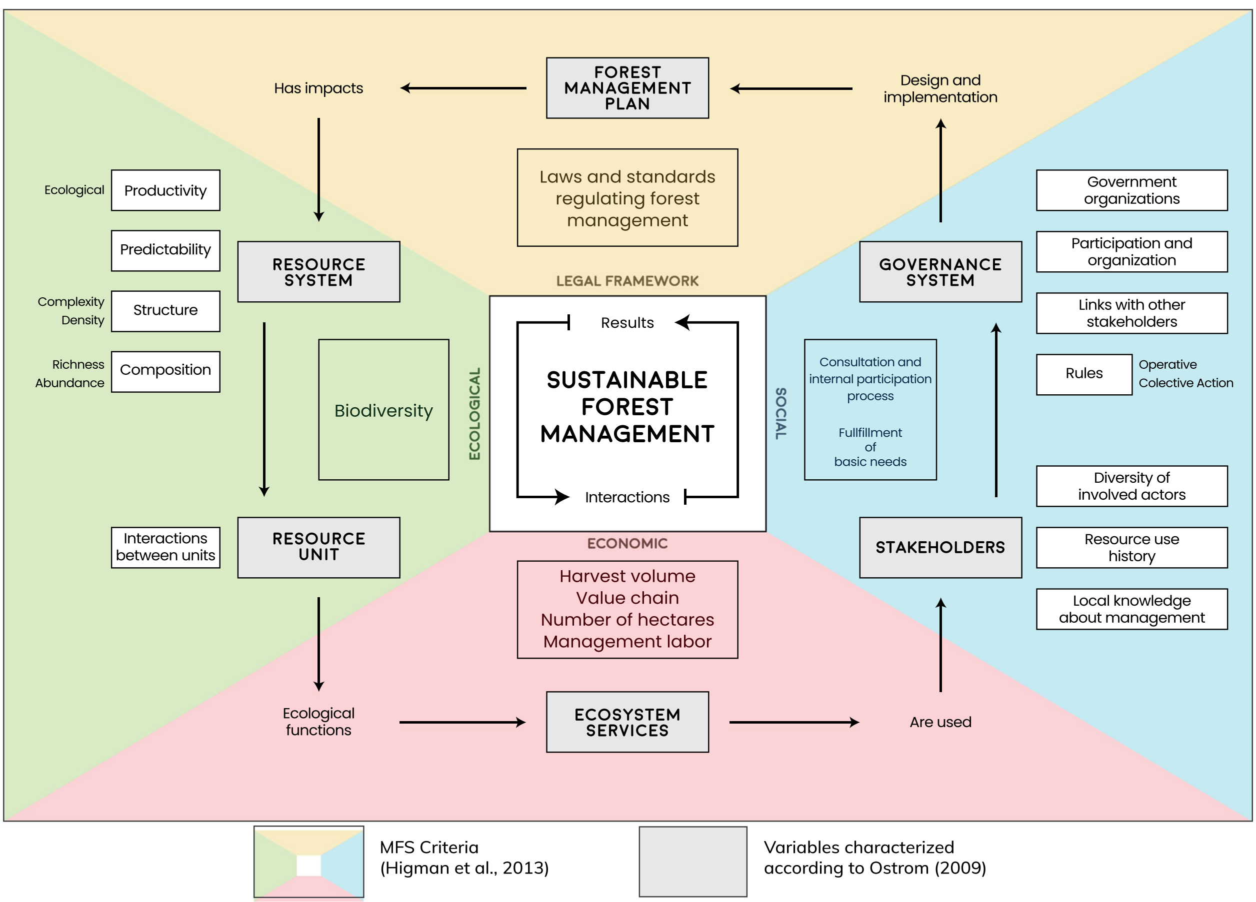

Fig. 2 Integrated model for the analysis of managed forest socio-ecological systems in central Mexico

generally not paid. This community work serves as a basis for the maintenance and development of infrastructure, public services, forest protection is maintained, and reforestation (Sánchez-Nupan 2020). According to constitutional regulations in Mexico, both *ejidos* and forest communities have the authority to design RS management strategies. Most Latin American countries promote community forest management as one of the strategies to achieve sustainable, equitable, and participatory forest management. This represents about 16% of all forests in the region; however, in Mexico the percentage of forests under community rights approaches 70% (Spilsbury and Kaimowitz 2002). The *ejido* is the institutional platform for the governance of shared resources and, at the same time, is the ideal territorial unit for analyzing the sustainability of forest ecosystems (Monroy-Sais et al. 2016). The institutional agreements set by system stakeholders generate social interactions that determine management practices for resource use and conservation. This creates a feedback cycle involving all the socio-ecological system components: resource system, resource units, governance system, and stakeholders, this feedback is the baseline proposal on which the managed SES are built (adapted on Ostrom 2007, 2009).

The interactions between internal (local) and external stakeholders allow the local application of constitutional regulations regarding the use of local forest resources. These are included in the forest management plan, a regulation endorsed by the federal environmental authority that sets the volumes of timber and non-timber products that can be exploited, as well as the timing to do so. The governance of forest SES in central Mexico involves the interaction of governmental and non-governmental institutions, the private sector, and civil society, based on the rules and regulations established by customary and statutory laws resulting from governance (Varma et al. 2000; Bray et al. 2007). It can work in both directions. For instance, the legal framework affects the institutional framework and instruments, while locally approved instruments can also initiate appropriate laws and institutions at both regional and national levels (Antinori and Rausser 2007; Sánchez-Nupan 2020).

The participation of external stakeholders (especially suppliers of technical forestry services; government officials from the environmental, forestry, and agricultural sectors; and academics) has been important in defining the different uses of the territory, in addition to influencing the development of some internal rules for the technical management and exploitation of timber and non-timber RSs and RUs (Bray et al. 2007; Sánchez-Nupan 2020). The setting of internal organization rules depends basically on local communities, which through customs and traditions have maintained a relative autonomy thanks to internal cohesion and intra-community trust. These rules can also be extended to external stakeholders, who develop, transform, and enforce the rules and regulations governing RSs and GSs (Ostrom 2007). The monitoring and subsequent evaluation of the ecological response to management decisions are essential in the relationship between ecological science, management, and environmental policy, as well as the quality and amount of services supplied by the system.

The autonomy of community stakeholders in the development of internal rules is noteworthy and depends directly on social cohesion and the existence of locally legitimized bodies to settle disputes and reach agreements (Antinori and Rausser 2007; Sánchez-Nupan 2020). The body in charge of these topics is the General Assembly (of the *ejido* or rural community), where relevant aspects of collective life are discussed and resolved, including forest management and use strategies. These strategies should be formulated from the available technical and scientific information and in compliance with the constitutional rules governing the use and management of forest resources.

Resource Use and Management Practices

Forest management can involve technical (treatment and tasks), institutional, and communication initiatives to produce timber and non-timber resources (Jardel 2015; Zerecero and Pérez 1981). Community forest management also varies greatly according to the social and political power that communities wield in the forests. At the highest level of management power, communities not only plan the management of their forests, but are also in charge of implementing that plan. At a lower level, communities may have the power at least to participate in the planning process, less management power may entail the responsibility to implement some aspects of management plans that were established elsewhere, such as planting trees and pruning at specified intervals. A management plan integrates social, economic, ecological, and legal information, which translates into concrete actions to be executed in the territory and clearly defined portions of RSs within a specific time (e.g., harvesting cycles of up to 50 years) (Fig. 2); this may change species distribution, and may cause local extinction of species, and ecological simplification (Jardel 2015). Management practices are those actions and measures driven by prior knowledge, cultural and technical heritage, perception, and beliefs. Although the actions have scientific and legal bases, the use of RSs (for timber and non-timber materials) has been largely driven by economic interests. The Resource systems tier was labeled composition, structure, and functions and shows that the Mexican temperate forest ecosystem represents about 17% (34 million ha) of the country (195 million ha). In terms of plant diversity, these forests host around 7000 species, practically a third of the national flora. Currently, 49 species of *Pinus* and 161 of *Quercus* are recognized in Mexico's forests; in the global context, Mexico has the second-highest diversity for each genus. The criteria for biodiversity conservation were incorporated only seven years ago. By constitutional rule, there are two types of forest management in Mexico, and these differ in harvesting intensity: lower in the Mexican Method for Managing Irregular Forests (IFM) and higher in the Silvicultural Development Method (MDS). The relationship between management practices and ecosystem services varies according to the RS and silvicultural practices, as well as the local environmental and economic conditions and the institutional agreements in each specific location (Fig. 2).

The choice of silvicultural method depends on the RUs derived from each specific ecosystem and dominant species, as well as on the volume of timber to be harvested. The management plan designed at the level of *ejido* or forest community is pivotal in achieving sustainability, and its application requires local stakeholders to adopt and apply it continuously; development and compliance contribute to legitimizing the links of the local community with external stakeholders (suppliers of technical forest services and officials of government agencies, basically) directly and indirectly involved in forest exploitation (Fig. 2). Community forest management can be very successful: important forest areas are conserved, the quality of life of marginalized peoples has improved, and democratic governance of forest commons has been favored. Stable incentives have been created for local commitment to conservation.

The Resource units tier was labeled Resources and shows a diversity of species harvested in the provision of wood. In many communities, wood is one of the few forest values recognized by existing markets, but government do not recognize the community's rights to the commercial use of this resource. Until now, forest management has been based on timber extraction from a few species of commercial interest, resulting in losses of other forest resources, local extinction of non-commercial species, and reduction of biodiversity (Galicia et al. 2018). Thus, traditional forest management promotes the supply of a few ecosystem services, affecting directly or indirectly the supply of multiple relevant services. These practices produce effects within the SES that affect interrelationships and directly disrupt a complex set of biophysical, ecological, and social characteristics that are essential for the resilience and sustainability of ecosystem services (Fig. 2). For instance, the adaptive level of ecosystems maybe be constrained through compliance with rules and regulations to limit or mitigate deterioration (timber extraction) and support the maintenance of forest ecosystems (replanting) (Fig. 2); a greater emphasis should be placed on the link between ecosystem theory and economic outcomes.

Socio-ecological Systems and Ecosystem Services

The temperate forests of Mexico provide direct ecosystem services (wood, fiber, firewood) to about 18 million people who live in 9200 rural communities. In addition, they offer more than 20 regulation and cultural ecosystem services that benefit many sectors of society. The important ecosystem services provided by forests in central Mexico are provisioning, regulating, and supporting services. These components are relevant in the RSs and RUs and are nested as shown in Table 1. According to the perception of stakeholders directly in charge of forest management in the study area, the most important was regulation of soil, water, and clean air; this was followed by supplies of food (fungi and wild fruits), habitat for wildlife and medicinal plants, and timber and firewood (Galicia and Zarco-Arista 2014). Monitoring the behavior of specific RS variables such as productivity (ecological and economic), structure (complexity and density), and composition (richness and abundance) throws light on the interactions of the RUs that regulate the maintenance of ecological functions essential to ecosystems and social systems by producing various ecosystem services (Fig. 2). For example, silvicultural practices can enhance the ES related to timber production (raw material). From 1990 to 2012, national timber production has ranged between a minimum of 6.3 million m^3 in 1995 and a maximum of 9.43 million m^3 in 2000. The provision of timber is the main beneficial ecosystem service provided by Mexican temperate forests since it accounts for 93% (US $1.336 million) of the overall value of forestry in Mexican forests. Pine plantations are among the most productive crop systems in temperate areas, having the highest C-storage potential in soil and tree biomass, with the understory and herbaceous vegetation contributing to a lesser extent (Peichl and Arain 2006). Therefore, Mexican temperate forests also provide important ecosystem regulators. Forests and their soils store about 45% of the terrestrial carbon, and act as a crucial sink for anthropogenic carbon emissions. The highest tree biomass (372 Mg ha^{-1}) has been measured in the monospecific forest of *A. religiosa* (75 years old) (Mendoza-Ponce and Galicia 2010). Temperate forest ecosystems have fertile soils of volcanic origin; more than 50% of these have andosol soils, followed by lithosols (28%), regosols (18%), and phaeozem (13%), and are rich in organic matter. In particular, andosols display a high accumulation of carbon, which is explained by the stabilization of soil organic matter with minerals of low structural order and the formation of organometallic compounds (Gamboa-Cáceres and Galicia 2012); this stabilization is highly resistant to decay, resulting in a very long residence half-time and a low C circulation (Gamboa and Galicia 2011). However, forestry intervention can have an undesired effect on water-flow regulation services (Castro-Torres 2020). For example, forest management in MDS aimed at high levels of runoff production, decrease in infiltration, produce adverse hydrologic or ecosystem effects (e.g., flooding) and soil erosion (Návar 2011; Castillo et al. 2012). The perception and social assessment of the availability (quantity and quality) of ecological functions and ecosystem services by the stakeholders using them may trigger a new decision-making process for RS management and its interaction with other regional

RSs, thus leading to a dynamic, and therefore adaptive, management cycle.

In the region of study, particularly in *ejidos* or forest communities, forestry laws and the timber market are exogenous variables that have a major influence on the dynamics of the forest SES analyzed. The specific ecological and social conditions of each *ejido* also affect the status of the ecosystem and the flow of ecosystem services. Although a given ecosystem provides more than one service, the current dynamics of SES is focused on improving the efficiency of one or two specific services (usually provision), thus positively or negatively affecting the availability of the rest (Castro-Torres 2020). MDS treatments decreased the density and size range of individuals and increased above-ground biomass, basal area, diameter, and average height. In concentrating on increased timber production and, in turn, carbon capture and storage capacity, MDS has resulted in the homogenization of the structure and composition of stands and has thereby reduced the ecological niches in the forest (Monárrez-González et al. 2018). On the other hand, selective logging under IFM maintains a more diverse and complex forest structure and composition, enhancing habitat conservation (Flores-Peredo and Vázquez-Domínguez 2016). The relationships between the structure of vegetation and wildlife that are observed in forests have been determined by the interaction between the biotic and abiotic elements needed to sustain the fauna in these ecosystems (Chávez-león et al. 2004; Guzmán-Mendoza et al. 2020). Therefore, the identification, quantification, and valuation of multiple ecosystem goods and services at sites under forest use is essential for the implementation of social, economic, and environmental policies for long-term ecosystem management (Bennett et al. 2009).

The flow of ecosystem services is the result of interactions between the governance system and the resource system through forest management practices implemented in the SES (Fig. 2). Ecosystem services are a utilitarian interpretation of the ecological functions of an ecosystem involving the use and valuation by the social system aiming to benefit its stakeholders (Egoh et al. 2007; Perevotchikova 2020; Rodríguez-Robayo et al. 2020). The local stakeholders involved in resource management in these *ejidos* identified and classified the benefits provided by the forest according to their perceptions; despite the different viewpoints, they concurred in the relevance ranking they assigned to the benefits. The services classified as most important were soil, water, and air regulation services; these are perceived as essential for forest community's well-being and forest productivity. Local stakeholders find it difficult to dissociate the provision of timber from other regulation services. Therefore, the interpretation of ecosystem services derives from social processes such as governance, institutions, and community empowerment (Fig. 2) (Castro-Torres 2020; Sánchez-Nupan 2020).

The management plan materializes a decision-making process and a set of rules that underpin silviculture and enable local development from the use of forest resources and ecosystem services (Fig. 2) (Castro-Torres 2020; Sánchez-Nupan 2020). The model identifies the key driver of the transformation, preservation, and/or implementation of the new technical interventions that are discussed and agreed upon by the local actors with the support of external stakeholders (technical services providers and government officials) (see Fig. 2, right); its dynamic component is derived from the management plan–RU relationship and the ES (quantity and quality) scientifically measured or socially perceived by the local stakeholders (Castro-Torres 2020; Sánchez-Nupan 2020). This is how an adaptive management cycle of forest socio-ecological systems is formed.

Discussion

Contribution to the Model

The integrated framework is a visual and pragmatic tool designed to identify through the linked trails within the conceptual framework how to move from the starting point to the outcome of interest (e.g., ecosystems services, sustainable forestry practices, and improvement of forest management plan) and to consider direct and indirect effects on other aspects of the SES. The criteria used for the model parametrization from the three theoretical approaches define and characterize the essential SES elements. They are related to evaluable processes to improve forest management; these can be quantitative or qualitative ecological and social variables (Mäkelä and Valentine 2020; Roopsind et al. 2018). Our research underlines the value of combining the frameworks that investigate social and ecological systems explicitly aiming to improve forest management in *ejidos* and local communities in central Mexico to achieve sustainability. This model can give rise to hypotheses regarding interactions between the components of environmental and social subsystems based on incorporating empirical information of study cases reported in the literature with a solid theoretical and methodological support; this can help to translate descriptive and explanatory concepts and variables into the complex interactions between societies and forest ecosystems. The construction of the model for *ejidal* or community forest management enables a theoretical and operational hierarchical ranking of the interrelationships between the various components and allows analysis of the impacts of the current management processes, including forest management. Integration of the different frameworks, particularly the social and ecosystem components, identifies elements related to specific socio-ecological contexts that may explain the dynamics of forest communities in central Mexico. It contributes to the analysis and understanding of three types of interaction and interrelationships in the SES in this region. First, the national policies are tailored to the local conditions through collective decisions mediated by external stakeholders (forest technicians), who contribute to the adoption and application of the technical rules of community forest operation. Second, the interactions that take place at different levels within the framework of governance systems define the operational selection decisions of the local communities (i.e., the timber extraction methods and dynamics and their outcomes in economic and ecological terms) through the impacts observed in the provisioning and maintenance of ecosystem services. The result of this conceptual and analytical integration exercise suggests that it can be used as an indicator of sustainability since it includes information that considers the social and economic relevance of conserving RSs over time for users, as well as the silviculture techniques and practices used to exploit timber and non-timber products (Galicia and Zarco-Arista 2014). The framework of the socio-ecological system proposed here integrates ecosystems and the goods and services produced by them with management and policies through monitoring and assessment as key aspects to conceptualize these relationships. At the same time, the model provides relevant information for the development of new interdisciplinary scientific reasoning while aiming to contribute to the resolution of complex forest SES problems with a pragmatic assumption (Oh and Oh 2011). This is a fundamental requirement for modeling socio-ecological trajectories and simulating scenarios in seeking to improve decision-making in the management of forest ecosystems at local, regional, or national levels (Levin et al. 2013; Martone et al. 2017).

The application of management techniques in forest ecosystems involves dilemmas that may have economic and ecological consequences since the preponderance of a particular action—in this case, timber extraction—reduces the economic diversification of the communities living in the forest and affects ecosystems. Timber extraction and food production adversely affect support services (Jujnovsky et al. 2012; Saynes et al. 2012). On the other hand, the management of non-timber forest resources allows people living in forest areas to obtain other benefits and safeguard the regeneration of forests (Christensen 1997; Winfree and Kremen 2009). Temperate forest ecosystems contribute to a set of strategic services (such as soil stabilization, conservation of the hydrological cycle and biological diversity, water and carbon uptake, and climate regulation), and meet the tangible and intangible needs and desires of human societies. Therefore, it is essential to promote multipurpose forest management strategies that enable the commercial use of timber while contributing to the maintenance of multiple ecological functions over time. The multifunctionality of ecosystem services entails interactions and relationships in the context of the social systems in which the management practices are operating. The diversity-resilience-sustainability triad is the key to multipurpose forest management (Rodríguez and Torres-Sorando 2001; Bender et al. 1998; Hiebeler 2000). Therefore, the identification, quantification, and valuation of multiple ecosystem goods and services at sites under forest exploitation are essential for the implementation of social, economic, and environmental policies regarding long-term ecosystem management strategies (Bennett et al. 2009). Analysis of the status of sustainability actions requires a focus not only on local collective actions by the direct users of a shared resource (e.g., population size, asymmetric power relations, diversification of livelihood options) and on local economies (e.g., change in demand or harvest sizes), but also on processes and participants operating at different levels. Finally, we propose the application of the community forest sustainability concept; this should relate not only to yields of timber and non-timber forest resources but also to the implementation of conditions for communities to improve their governance systems, the state of their resources, institutional interactions, and the ecosystem services provided by forests. This will only be possible by determining the costs of ecosystem use and management practices needed to increase the supply of services, and by understanding the decisions and motivations of forest owners.

Conclusions

The major and more general material components of the model proposed here have been integrated from the in-depth study of three analytical frameworks that address the interaction between social and ecological systems using the grounded theory approach that enables comparison of data with data, data with concepts, concepts with concepts, and theoretical categories with theoretical categories (Charmaz 2001). Also, the framework emphasizes the interconnectedness between three frameworks of sustainability to enable better outcomes for ecosystem services derived from forest management in particular socio-environmental contexts and sector-specific goals. The macro components of the model constitute a framework that can be static and theoretically useful for revealing the causalities that may explain a certain condition or state of the socio-ecological system. However, the second- and third-level analytical variables will vary according to the context and SES characteristics. The advantages of the model developed here include the comprehensive organization and operationalization of variables from several analytical frameworks, which were successfully applied in forest *ejidos* in central Mexico. With the addition of site-specific empirical information, this will be a robust model for analysis of case studies of forest communities in Mexico.

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Compliance with Ethical Standards

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