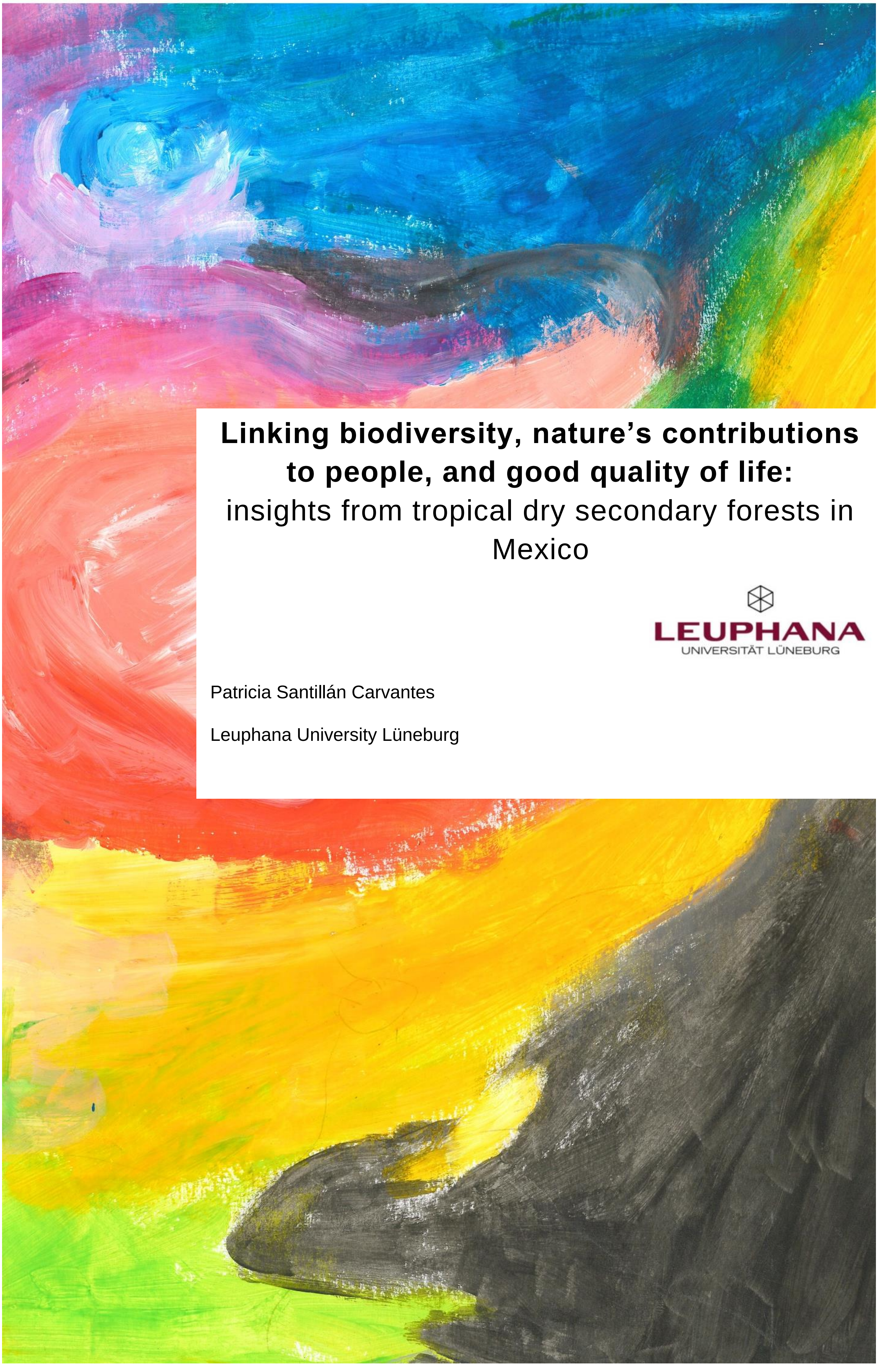

Linking biodiversity, nature's contributions to people, and good quality of life:
insights from tropical dry secondary forests in Mexico

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Linking biodiversity, nature's contributions to people, and good quality of life: insights from tropical dry secondary forests in Mexico

Faculty of Sustainability

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adentro
Nuestro corazón

(Nature, outside and inside, our heart)

A la niña curiosa de hace 20 años que se permitió soñar con esto
(To the curious little girl that 20 years ago allowed herself to dream about this)

TABLE OF CONTENTS

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PREFACE

I will tell you today a story, kind of a personal one. I was a curious girl passionate about nature. I lived in Mexico City, surrounded by beautiful mountains and volcanoes (e.g., the "Iztacíhuatl" and the "Popocatépetl"). I was in love with nature. I was still a girl when I discovered that I lived in Mexico, one of the most biodiverse countries in the world (Toledo 1999). Then I realized there was something "bad" happening that was destroying nature. I heard about the massive biodiversity loss that we as a country (Carabias et al. 2010) and as a world (Western 1992) were experiencing. I studied biology to be a "doctor for nature." However, things were worsening for biodiversity from the research perspective. I felt the pressure to act, to do something, anything. It was a personal matter, and I have been researching through grief and despair ever since (Macy 1995). As a teenager, I considered I could do something to IMPROVE the world, to SAVE the world from my trench in Science, and I crossed different studies with this mindset. I started my PhD thinking that I would transform the world, but the truth is that I transformed myself in a way that I would have never imagined. During this PhD, I relearned some things I was told as a biologist, such as making science as if the people were the "bad ones" for the biodiversity loss. I relearn to transform and question my inner values and assumptions. I dive into a transformational path to save myself and assume that there are no heroes in sustainability but teamwork. Maybe by this inner transformation, I am saving the world somehow; after all, everything and everyone is connected in this complex system called life. Therefore, this thesis intends to launch sparks of hope from the Social-Ecological systems approach.

LIST OF PAPERS

4. Patricia Santillán-Carvantes, Berta Martín-López, Manuel Pacheco-Romero, Maraja Riechers, Patricia Balvanera. Monitoring social-ecological systems dynamics: an analytical framework. Under review in *Ecology and Society* journal.

5. Patricia Santillán Carvantes, Patricia Balvanera, Simon Thomsen, Francisco Mora, Nathalia Pérez-Cárdenas, Daniel Cohen-Salgado, Rubén Ramírez Ramírez, Mayra E. Gavito, Berta Martín López. 2023. Spatial characterization of social-ecological systems units for management in Tropical Dry Forests*. Landscape ecology* https://doi.org/10.1007/s10980-023-01714-x

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ADDITIONAL PUBLICATIONS

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LIST OF ABBREVIATIONS

EESV	Essential Ecosystem Services Variables
IPBES	The Intergovernmental Platform on Biodiversity and Ecosystem Services
MA	Millennium Ecosystem Assessment
NCP	Nature’s Contributions to People
QoL	Quality of life
SES	Social-Ecological Systems
SESU	Social-Ecological System Units

TDF Tropical Dry Forest

LIST OF FIGURES

ABSTRACT

One of the key challenges of our era is to halt biodiversity loss and foster the sustainable use of nature. The Sustainable Development Goals (SDGs) recognize the importance of the inextricable link between social and ecological systems and human quality of life (QoL) and biodiversity. Therefore, understanding the feedback and interactions between biodiversity, nature's contributions to people (NCP), and QoL plays a central role in advancing toward sustainability. In this context, the social-ecological systems (SES) approach has advanced on the subject, particularly in recent decades; however, much remains to be done to comprehensively understand these relationships and interactions, especially at local decision-making scales. In this thesis, through the lenses of the SES approach, I investigate connections between biodiversity, NCP, and QoL in a tropical dry forest (TDF) on the Western coast of Mexico. This place is one of the best-known Neotropical TDF and has been the focus of SES research in the past 20 years, making it an excellent case study for exploring these connections.

First, to approach the need for dialogue among different global and local scales and between global and local frameworks, the thesis identifies five key components of the SES dynamics-(1) ecological supply, (2) co-production of NCP, (3) management, (4) demand, and (5) benefits- and three local decision-making scales of analysis- individual plot, smallholder, and land tenure or governance units. A literature review was performed on the social-ecological indicators for the last 11 years in the Chamela-Cuixmala region to operationalize this framework. The representability of the framework shows that research has emphasized the components of NCP co-production (42% of indicators) and SES management (21%). By analyzing SES dynamics through this new framework, we can support the monitoring of NCP and potentially detect regime shifts or radical changes before they happen. The framework is simultaneously context-specific and operationable across global contexts, providing an opportunity to inform discussions on global sustainability from local contexts.

Second, this thesis uses social-ecological information to identify social-ecological systems units (SESU) spatially explicitly. A methodology was provided to spatially identify the components of social-ecological systems that environmental conditions and management practices have shaped at three previously stated relevant decision-making scales: plots owned by individuals, plot owners, and governance units. To do so, we identified and characterized: (1) ecological clusters (EC), (2) social-management clusters (SC), and (3) SESU in a TDF in western Mexico. Our findings suggested that decision-makers (*ejidatarios*, i.e., type of ownership (related to agrarian reform), that in most cases the land allocated is small-smallholders-) are bounded by the topographical characteristics and the public policies that determine communal (or private) governance and the number of resources available to them. The methodology can be applied to other contexts and nested decision-making scales. The spatial identification of these interdependencies is critical for landscape planning since it can contribute to reconciling productive activities and biodiversity conservation.

Finally, the thesis examines the self-perceived QoL across the different SESU, finding 48 QoL items, which were grouped into six categories: 1) social capital, 2) economic capital, 3) agency, 4) nature, 5) peasant non-work activities, and 6) government and services; and two additional dimensions referred to obstacles and enablers of QoL. We found that the more land cover transformation, the more enablers, and obstacles of QoL are identified; emphasis was put on economic capital to achieve QoL. As management is intensified and governance fosters individualism across SES, the higher the Current Welfare Index, and the lower the self-perceived material and non-material satisfaction. We discuss the need for governance structures promoting smallholders´ worldviews that move beyond utilitarianism and foster commons. The social-ecological systems approach employed throughout this dissertation contributed towards crosscutting insights; the testing of new frameworks and methodologies represent important steps towards unraveling the connections between biodiversity, NCP, and QoL and contributes to achieving sustainable scenarios such as the ones proposed by the SDGs.

ZUSAMMENFASSUNG

Eine der größten Herausforderungen unserer Zeit besteht darin, den Verlust der biologischen Vielfalt zu stoppen und die nachhaltige Nutzung der Natur zu fördern. Die Ziele für nachhaltige Entwicklung (SDGs) erkennen die Bedeutung der untrennbaren Verbindung zwischen sozialen und ökologischen Systemen sowie zwischen der menschlichen Lebensqualität (QoL) und der biologischen Vielfalt an. Daher spielt das Verständnis der Rückkopplungen und Wechselwirkungen zwischen der Artenvielfalt, den Beiträgen der Natur zum Menschen (NCP) und der Lebensqualität eine zentrale Rolle bei der

Weiterentwicklung in Richtung Nachhaltigkeit. In diesem Zusammenhang hat der Ansatz sozial-ökologischer Systeme (SES) insbesondere in den letzten Jahrzehnten zu diesem Thema Fortschritte gemacht, es bleibt jedoch noch viel zu tun, um diese Beziehungen und Interaktionen umfassend zu erfassen, insbesondere auf lokaler Entscheidungsebene. In dieser Arbeit untersuche ich anhand des SES-Ansatzes Zusammenhänge zwischen Biodiversität, NCP und Lebensqualität in einem tropischen Trockenwald (TDF) an der Westküste Mexikos. Dieser Ort ist einer der bekanntesten neotropischen TDF und stand in den letzten 20 Jahren im Mittelpunkt der SES-Forschung, was ihn zu einer hervorragenden Fallstudie für die Erforschung dieser Zusammenhänge macht.

Um zunächst auf die Notwendigkeit eines Dialogs zwischen verschiedenen globalen und lokalen Ebenen sowie zwischen globalen und lokalen Rahmenbedingungen einzugehen, identifiziert die Arbeit fünf Schlüsselkomponenten der SES-Dynamik: (1) ökologische Versorgung, (2) Koproduktion von NCP, (3) Management, (4) Nachfrage und (5) Nutzen – und drei lokale Entscheidungsskalen der Analyse – einzelnes Grundstück, Kleinbauern und Landbesitz- oder Governance-Einheiten. Zur Operationalisierung dieses Rahmenwerks wurde eine Literaturrecherche zu den sozial-ökologischen Indikatoren der letzten 11 Jahre in der Region Chamela-Cuixmala durchgeführt. Die Darstellbarkeit des Rahmens zeigt, dass die Forschung auf den Komponenten NCP-Koproduktion (42 % der Indikatoren) und SES-Management (21 %) fokussiert hat. Durch die Analyse der SES-Dynamik mithilfe dieses neuen Rahmenwerks können wir die Überwachung von NCP unterstützen und möglicherweise Regimewechsel oder radikale Veränderungen erkennen, bevor sie stattfinden. Das Rahmenwerk ist gleichzeitig kontextspezifisch und in globalen Kontexten einsetzbar und bietet daher die Möglichkeit, Diskussionen über globale Nachhaltigkeit aus lokalen Kontexten zu bereichern.

Zweitens nutzt diese Arbeit sozial-ökologische Informationen, um sozial-ökologische Systemeinheiten (SESU) räumlich explizit zu identifizieren. Es wurde eine Methodik bereitgestellt, um die Komponenten sozial-ökologischer Systeme räumlich zu identifizieren, die sowohl durch die Umweltbedingungen als auch durch Managementpraktiken auf drei zuvor genannten relevanten Entscheidungsebenen geprägt wurden: Grundstücke im Besitz von Einzelpersonen, Grundstückseigentümer und Verwaltungseinheiten. Zu diesem Zweck identifizierten und charakterisierten wir: (1) ökologische Cluster (EC), (2) Social-Management-Cluster (SC) und (3) sozial-ökologische Systemeinheiten (SESU) in einem TDF im Westen Mexikos. Unsere Ergebnisse legen nahe, dass Entscheidungsträger (ejidatarios, d. h. Kleinbauern) durch die topografischen Merkmale und die öffentlichen Richtlinien, die die kommunale (oder private) Regierungsführung bestimmen, sowie durch die Anzahl der ihnen zur Verfügung stehenden Ressourcen begrenzt sind. Die Methodik kann auf andere Kontexte und verschachtelte Entscheidungsskalen angewendet werden. Die räumliche Identifizierung dieser Wechselwirkungen ist für die Landschaftsplanung von entscheidender Bedeutung, da sie dazu beitragen kann, produktive Aktivitäten und den Schutz der biologischen Vielfalt in Einklang zu bringen.

Schließlich untersucht die Arbeit die selbst wahrgenommene Lebensqualität in den verschiedenen SESU und findet 48 Lebensqualitätselemente, die in sechs Kategorien gruppiert wurden: 1) Sozialkapital, 2) Wirtschaftskapital, 3) Entscheidungsfreiheit, 4) Natur, 5) bäuerliche Lebensqualität und Arbeitsaktivitäten und 6) Regierung und Dienstleistungen. Zwei zusätzliche Dimensionen bezogen sich auf Hindernisse und fördernde Faktoren der Lebensqualität. Wir haben festgestellt, dass je stärker sich die Landbedeckung verändert, desto mehr Faktoren (Hindernisse und fördernde) für die Lebensqualität identifiziert werden. Der Schwerpunkt wurde auf ökonomisches Kapital gelegt, um die Lebensqualität zu erreichen. Je intensiver das Management und die Governance den Individualismus im gesamten SES fördern, desto höher ist der aktuelle Wohlfahrtsindex und desto geringer ist die selbst wahrgenommene materielle und immaterielle Zufriedenheit. Wir diskutieren die Notwendigkeit von Governance-Strukturen, die die Weltanschauungen von Kleinbauern fördern, die über den Utilitarismus hinausgehen und das Gemeindgut fördern. Der in dieser Arbeit verwendete sozial-ökologische Systemansatz trug zu übergreifenden Erkenntnissen bei, die Erprobung neuer Rahmenwerke und Methoden stellt wichtige Schritte zur Aufklärung der Zusammenhänge zwischen Biodiversität, NCP und Lebensqualität dar und trägt zur Verwirklichung nachhaltiger Szenarien bei, wie sie in den SDGs vorgeschlagen werden.

CHAPTER I. FRAMEWORK PAPER

"The colors of my PhD" Patricia Santillán Carvantes. October 2021

1. INTRODUCTION

Sustainability science wants to answer the vital question: "At multiple scales and over succeeding generations, how can the earth, its ecosystems, and its people interact towards the mutual benefit and sustenance of all?" (Weinstein 2010). Kates et al. (2001) formally refer to sustainability science as a new discipline seeking real-world solutions to complex environmental problems. However, its origin dates back to the early environmental movements in the US, including the brave woman Rachel Carson, who first argued that pesticides were dangerous for people's and nature's health (Carson 1962). Since then, research has documented increasing damage to the intensive human activities on biodiversity (Altieri 1991) and ultimately on human quality of life (MA 2005). Sustainability science arose then to understand the complex dynamics between humans and environmental systems with research based on conceptual models and methods from different disciplines and ontologies (Spangenberg 2011), assuming that the problems we are facing are complex and non-linear responses can be expected (Scheffer and Carpenter 2003). Sustainability science is also recognized as a cornerstone to progress towards sustainability and an "opportunity to bring science closer to the people" (Spangenberg 2011 p. 1) and the people closer to the science. For such an endeavor, sustainability science requires different perspectives, disciplines, philosophies, and methodologies through multidisciplinarity (i.e., several disciplines working parallel, with limited interaction, on a shared objective usually predefined by researchers); through interdisciplinarity (i.e., researchers from different disciplines working together in a co-defined objective, in a way that their results can be integrated); and transdisciplinarity,(i.e., a demanding form of knowledge integration that co-identifies the problem together with different disciplines and sectors of society) (Spangenberg 2011). Through these different perspectives, a wide variety of sustainability sciences disciplines have arisen to tackle in their own way sustainability issues.

In this history of disciplines and perspectives, efforts to protect biodiversity were guided by a changing rational. During the 60s-70s, the framing of conservation was to protect Nature for itself, and the red list of species was created, as well as protected areas intended to leave humans outside to "avoid any damage to ecosystems" (Mace et al. 2012). During the 80s and 90s, the paradigm was to protect nature despite people, and huge research started documenting the threatened species and habitat loss changes. In this century, 2000-2005, the frame became to protect nature for people. The Millenium Ecosystem Assessment (2005) clearly stated all the benefits people obtain from nature, and therefore the Ecosystem Services concept arose, and the economic valuation of nature was fostered. Since 2010, the focus shifted to conserving social and ecological systems. It emphasized the complex feedbacks and interactions between social and ecological systems (Bennett et al. 2015, Díaz et al. 2015). Then, the social-ecological systems perspective was recognized as a key approach in sustainability science to maintain biodiversity while conserving people's good quality of life (Fischer et al. 2015).

This thesis adopts an interdisciplinary perspective to address the core question of sustainability and promote harmonic relationships between humans and biodiversity from the social-ecological systems approach. By adopting a social-ecological systems approach, this thesis investigates new approaches and new data sources for analyzing biodiversity, nature's contribution to people (NCP) and quality of life (QoL), and their interactions at multiple scales in the Chamela-Cuixmala region, a hotspot biodiversity area with profound social challenges. In the following, I begin by outlining the theory of social-ecological systems and how the links between People and Nature, and NCP and QoL fit into the theoretical framework that forms the foundation for this dissertation. I highlight the outstanding research gaps that this thesis aims to address and introduce the research questions that guide each of the papers included in this thesis.

1.1 SOCIAL-ECOLOGICAL SYSTEMS (SES) FEATURES AND IDENTIFICATION

The concept of social-ecological systems (SES) tries to capture the complex and intertwined relationships between social and ecological elements across spatial and temporal scales and their interdependencies (Berkes, Folke, and Colding 1998; Ostrom 2009). This involves the dynamic interactions between societies and their environment, including cultural, political, economic, and governance factors (Chapin et al. 2009, Martín-López et al. 2017) and ecosystems, biodiversity, land, water, air, and other elements of nature that determine the conditions of people's livelihoods and that operate across scales. SES are considered complex adaptive systems in which interactions among the different elements can lead to emergent properties that cannot be predicted or explained by the properties of individual components on their own (Goldstein 1999). These systems can adapt and self-organize so that multiple configurations with different feedbacks and dynamics exist (Scheffer and Carpenter 2003).

SES possess key features that help to describe and understand the interrelatedness of social and ecological processes. Such features include feedback loops, resilience, cross-scale dynamics, recognition that humans depend on nature, and adaptive governance and policy frameworks. Feedback loops can be positive (amplifying) or negative (dampening) interactions that drive the system's dynamics. Resilience is the capacity of a system to adapt to disturbances and changes in the environment (Berkes et al. 2002, Virapongse et al. 2016). Resilient social-ecological systems can cope with shocks and disturbances, recover from disturbances, and transform when necessary. Cross-scale dynamics recognize that SES operates at multiple scales, from local communities to regional, national, and global levels. Cross-scale dynamics refer to the interactions and interdependencies between these scales (Scheffer et al. 2001). The recognition that humans depend on nature is increasingly accepted in research, policy, and business. One of the pillars of SES is that human wellbeing is fundamentally linked to ecosystem integrity (Fischer et al. 2015). Finally, adaptive governance and policy frameworks involve flexible and inclusive decision-making processes and integrating SES research and diverse knowledge systems to promote sustainability. Despite the global recognition by policymakers of the social-ecological interactions, implementing these policies still falls short of what is necessary (Fischer et al. 2015).

This lack of implementation is related to a key knowledge gap (gap1): the need to operationalize new frameworks and methods for incorporating social-ecological feedback and dynamics (Mastrángelo et al. 2019). The different nature of social and ecological disciplines makes this a difficult endeavor. In an attempt to navigate the genuine complexity of SES, a variety of frameworks have been developed to analyze SES across time and space (Berkes et al. 1998, Folke et al. 2002, MA 2005, Liu et al. 2007, Ostrom 2009, Díaz et al. 2015). The different frameworks differ in their aims to inform upon certain aspects of SES and the people they are addressed for; for instance, the SES framework proposed by Berkes et al. (1998) aims to inform the study of local resource management practices and outcomes. It highlights the nested scales of management practices and the embeddedness of management in institutions. It addresses local managers' ability to maintain bottom-up organizational and resilience settings. In other frameworks, the analysis of SES explicitly recognizes the relevance of feedback, non-linearity, thresholds, time lags, legacy effects, path dependence, and emergent properties in shaping human–nature interactions (Liu et al. 2007, Biggs et al. 2021).

Ostrom's framework was developed as an explanatory framework for diagnosing common-pool resource management problems from an institutional and resilience perspective intended for resource users. This framework set up a cornerstone for SES research since it has been used for two main purposes, 1) to guide empirical data collection and analysis and 2) to provide a shared vocabulary of variables to facilitate cross-case comparisons and support interdisciplinary collaboration. Besides that, the Ecosystem Services framework from the Millennium Ecosystem Assessment (2005) further elaborates on the sustainable management of ecosystems among decision-makers. It emphasizes ecosystems' benefits to human well-being through four main ecosystem services: provisioning, regulating, cultural, and supporting. Finally, the IPBES framework was intended for global negotiations among decision-makers, emphasizing global and regional sustainability through nature's contribution to people (NCP) monitoring (Fig.1, Díaz et al. 2015, Palomo et al. 2016, Bruley et al. 2021). The objective of **Paper 1** is to develop and test an analytical framework to operationalize global frameworks, such as the IPBES one, at local decision-making scales in our case study in the Chamela-Cuixmala region on the West Coast of Mexico. The IPBES framework (Figure 1) plays a key role in this dissertation because it settles the basis of the theoretical assumptions on SES dynamics.

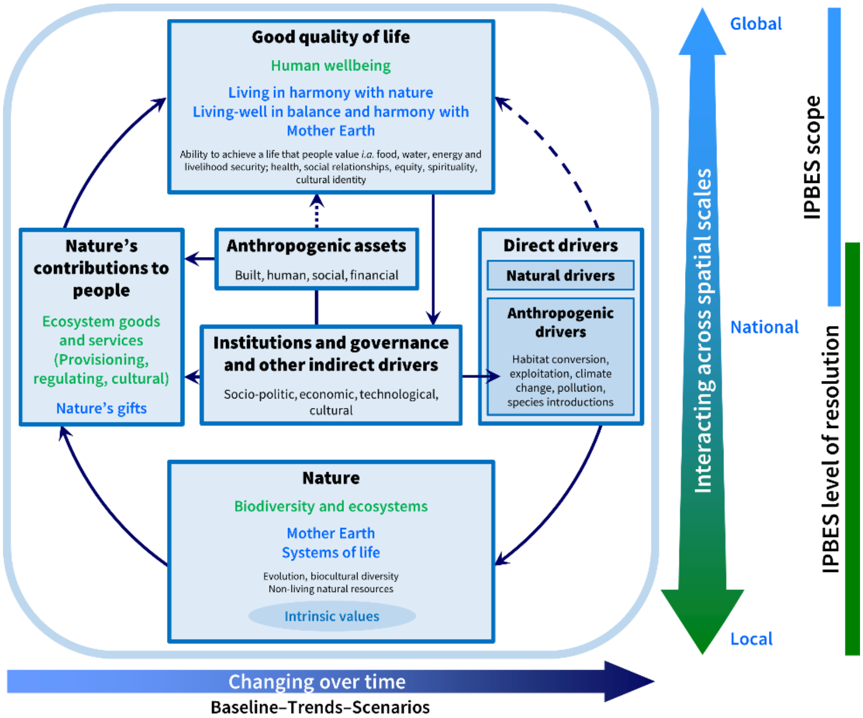


Figure 1. IPBES conceptual framework (Díaz et al. 2015) plays a key role in this dissertation because it settles the basis of the theoretical assumptions on SES dynamics.

Another key gap in SES research is the identification and delineation of SES boundaries in a spatially explicit way (gap 2). The main challenge for this aim is the different scales at which the social and ecological components operate (Cumming et al. 2006). Despite this challenge, recent examples of spatial identification include Hamann et al. (2015), who presented an approach to identify and map SES based on households' direct use of ecosystem services in South Africa. They found three different ecosystem services bundles mainly characterized by social factors such as household income, gender of the household head, and land tenure, and only partly determined by the supply of natural resources. Hanspach et al. (2016) developed a typology of social–ecological units based on land use patterns to develop strategies for biodiversity conservation. They found that biophysical conditions and especially topography frame the setting of cultural landscapes as a whole. Martín-López et al. (2017) provided a methodological framework to delineate boundaries of SES at the municipality scale and applied it in Southern regions of Spain. Its methodology consists of ecological regionalization, socio-economic regionalization, identification of social-ecological systems boundaries, and validation of boundaries through participatory mapping. Following such methodology, Lazzari et al. (2019) identified marine archetypes in Southern Spain. They found twelve coastal marine social-ecological systems that suggested a co-evolution of the social-ecological associations in these areas. Their results highlight the need to integrate each archetype's characteristics and conservation challenges. Vallejos et al. (2020) identified eight subclasses of social-ecological functional types (SEFTs) in El Chaco region in Argentina. The SEFT framework that they built is based on the ecosystem and agent functional types approaches to characterize administrative units hierarchically; by this methodological framework, they found that the degree of anthropization and the mean annual productivity were the variables that captured the most spatial variability of SEFTs. Pacheco-Romero et al. (2022) proposed a data-driven methodological routine based on multivariate statistical analysis to identify the most relevant indicators for mapping and characterizing SES archetypes in a particular region. They took Andalusia (Spain) as a case study, where they found 15 SES archetypes at the Municipality scale separated by variables such as crop and livestock production, net primary productivity, population density, land protection, and education level. Zarbá et al. (2022) operationalized South America's so-called SELS (social-ecological land systems) methodology by identifying five larger social-ecological regions in which 13 SELS were nested. They combined data-driven spatial analysis with a knowledge-based evaluation by an interdisciplinary group of regional specialists.

From these examples, it is clear that the spatial identification of different SES could help decision-makers and authorities to target areas with specific interventions that are best adapted to the area's particular sustainability challenges, to know and understand the specific dynamics at play in certain areas, natural resource use patterns, human well-being challenges, and conservation issues. Although the full complexity of SES can never be characterized by maps (Hamann et al. 2015), the definition of social-ecological units can help to contribute to landscape planning by spatially characterizing social-ecological dynamics. However, despite all these efforts, much of this research remains applied at large spatial scales such as Regional and Municipal. In **Paper II,** I (we) provide a methodology to intertwine different social and ecological data to identify social-ecological systems units (SESU) at the finest local governance scales previously identified in **Paper I**. In our case study, such scales correspond to the *ejido*, *ejidatario,* and *ejidal* plot. I will explain these scales further in the case study section.

1.2 THE LINK BETWEEN PEOPLE AND NATURE

Back in the 2000s, ecosystem services' great appeal was that they served as a link between people and nature. Today a broader definition is represented by the NCP. The introduction of the NCP concept emerged out of necessity to incorporate a wider and more diverse set of knowledge systems, worldviews, and stakeholders to strengthen the science–policy interface on people and nature by increasing inclusivity and plurality (Kadykalo et al. 2019). NCP encompass all "contributions, both positive and negative, of living nature (i.e., biodiversity of organisms, ecosystems, and their associated ecological and evolutionary process) to quality of life for people" (Díaz et al. 2018, p. 3). Accordingly, the concept of NCP encompasses the multiple ways people relate with, demand, and value nature and its contributions (Díaz et al. 2015, 2018, Pascual et al. 2017). NCP can be material, non-material, and regulating (Díaz et al. 2018).

One of the differences between ecosystem services and NCP is that ecosystem services are frequently referred to as a "free gift of nature" in scientific analyses and popular discourse (Spangenberg et al. 2014, Bruley et al. 2021); however, they are typically co-produced by social-ecological processes and demand human involvement to deliver a benefit (Palomo et al. 2016). The co-production of ecosystem services/NCP by people and nature has become more widely acknowledged since the Millennium Ecosystem Assessment (Mastrángelo et al. 2019). The IPBES framework puts the role of humans in providing NCP front and center through the anthropogenic assets because NCP are inextricably linked to the co-production process (Díaz et al. 2015). Despite this recognition, research on the co-production process remains elusive, and understanding how NCP are co-produced remains a key knowledge gap (gap 3, Bennett et al. 2015). **Paper I** in this dissertation develops and tests an analytical approach toward monitoring the co-production of NCP.

Institutions and governance play a key role in these co-production processes (Díaz et al. 2015), for example, through public policies regulating land use and management. Governance has generally been defined as a set of rules/policies, decision processes, and actors designed to steer a system toward some desired outcomes (Aggarwal and Anderies 2023). In fact, within the IPBES conceptual framework, governance and institutions play an integral role and affect NCP by regulating the access to, control over, and allocation of capital, contributing to the co-production of NCP (Díaz et al. 2015). The critical role of governance in addressing the complex challenges of SES is increasingly being recognized in scientific and policy discussions at multiple levels, yet, our understanding of what governance is and how we can foster the effectiveness of governance systems remains limited (gap 4, Bennett et al. 2015, Mastrángelo et al. 2019, Aggarwal and Anderies 2023). In **paper II** and **paper III**, I test different types of governance types (communal vs. individual) on the SES spatial representation and the quality of life (QoL) outcomes.

1.3 THE LINK BETWEEN NATURE'S CONTRIBUTIONS TO PEOPLE (NCP) AND QUALITY OF LIFE (QOL)

In the IPBES framework, good quality of life (QoL) is the accomplishment of a "fulfilled human life" (Díaz et al. 2015) and encompasses individual aspirations of access to food, water, health, education, and livelihood security; social goals of diversity of options, environmental justice, and intra- and intergenerational equity; and cultural dimensions of identity and autonomy, spirituality and religions, and arts and cultural heritage (Pascual et al. 2017, Bruley et al. 2021). Quality of life or human well-being (here indistinctly used as good quality of life) is a multidimensional concept with objective dimensions that include social and material attributes and subjective dimensions that comprise a person's assessment of their own conditions (Summers et al. 2012). It includes different social, environmental, physical, spiritual, and emotional components associated with how people function and feel. For the IPBES, the QoL categories include access to food, energy and water security, and physical, mental, and social health (Díaz et al. 2015). For the MA (2005), QoL has five constituents: security, the basic material for a good life, health, good social relations, and freedom of choice and action. These two typologies are by no means the only way to define QoL, a highly context-dependent concept influenced by many factors (Summers et al. 2012). However, these typologies are cornerstones for the NCP-QoL analysis from the policy interphase. In fact, the IPBES framework acknowledges the context-specific perspective of the human-nature relationship and the generalizing perspective, both included in the NCP notion. The context-specific perspective acknowledges the variety of viewpoints on NCP that exist throughout the world. It emphasizes how the same NCP can be viewed in many ways based on the individual's setting. The generalizing approach aims to define the 18 NCP that support people's quality of life irrespective of context.

Although there is a substantial body of literature on the indicators of human well-being, the link between people and nature is not well understood within the QoL literature (Summers et al. 2012). Scientists are progressively exploring conceptual and methodological frameworks for conducting socio-ecological analysis (King et al. 2014). Despite this increasing recognition of the interconnectedness between human's QoL and NCP among scientists, multiple ecosystem services/NCP contributions to the quality of life are still a key knowledge gap (gap 5) elusively addressed in the SES literature, particularly for non-monetary assets that form the basis of rural economies (Mastrángelo et al. 2019). **Paper III** of this dissertation aims to explore the QoL across different SESU previously identified and characterized in **paper II**.

1.4 KEY RESEARCH QUESTIONS

Based on the key gaps outlined in the previous sections, this dissertation's main research question is: How can management strategies foster biodiversity conservation, nature's contributions to people, and farmers' good quality of life in the context of a tropical dry forest?

The sub-research questions are:

1. How to operationalize global frameworks to monitor social-ecological dynamics across local decision-making scales?

2. How to spatially identify social-ecological systems that environmental conditions and management have shaped?

3. How does the quality of life differ for objective indicators and subjective self-perceptions across Social-Ecological System Units?

These questions are dealt with in the three papers included here. The conceptual focus area of each paper is indicated in Fig. 2 within the general IPBES theoretical framework guiding this thesis.

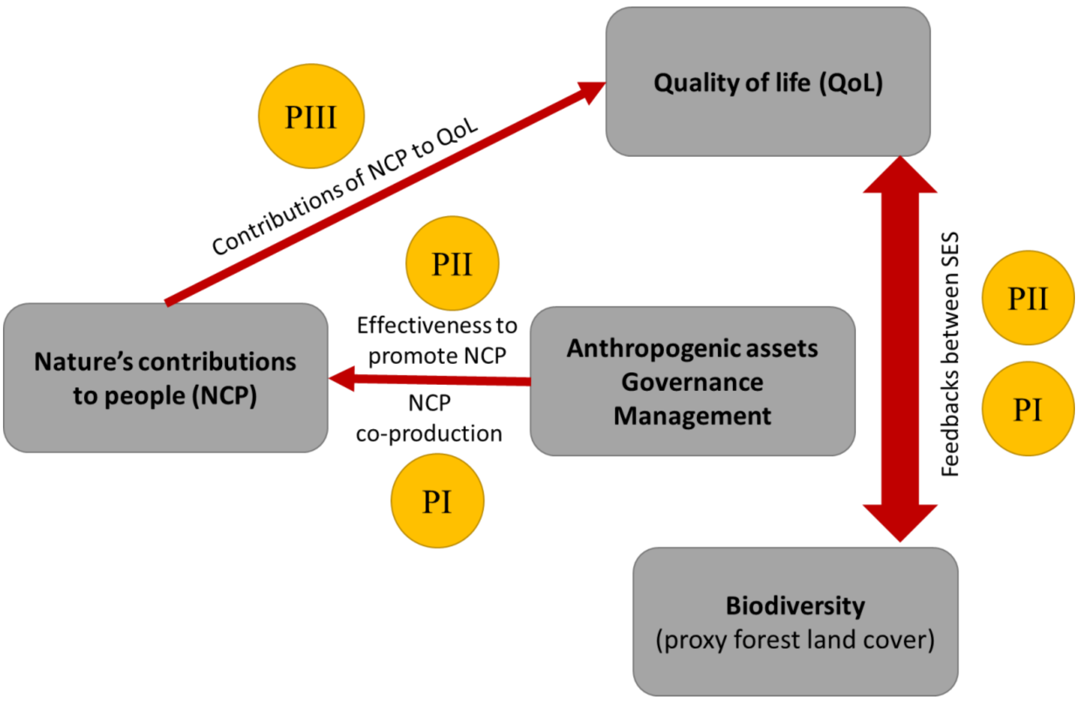


Figure 2. Main focus areas of the three research papers included in this thesis. **Paper I** theoretically deals with feedbacks between social and ecological systems, while **paper II** does it methodologically. **Paper II** also deals with the influence of governance on the effectiveness of promoting social-ecological change. **Paper III** empirically explores the contributions of social-ecological systems (based on NCP) to quality of life. This overview is based on the IPBES framework.

2. RESEARCH APPROACH

The research of this dissertation was developed in the context of a place-based Long Term Social-Ecological Research (LTSER) network with a case study in the Chamela-Cuixmala region (Balvanera et al. 2021). The Chamela-Cuixmala region is part of the tropical dry forest (TDF) biome located in the municipalities of La Huerta and Villa Purificación in the state of Jalisco along the Mexican Pacific coast (Ceballos and García 2010). It is a biodiversity hotspot area where research has been taking place for more than three decades (Maass et al. 2005, Castillo et al. 2018, Balvanera et al. 2021) with increasing SES research in the last decade, particularly guided by the ecosystem service framework (e.g., Balvanera et al. 2011, Castillo et al. 2018, Cortés-Calderón et al. 2021). The nearly 400 articles and 200 bachelor, master, and doctoral theses based on research from this area make it one of the better-studied sites in the Neotropics (Noguera et al. 2002, Castillo et al. 2018, Figure 3), which in turn makes it an excellent case study for the exploration of SES dynamics.

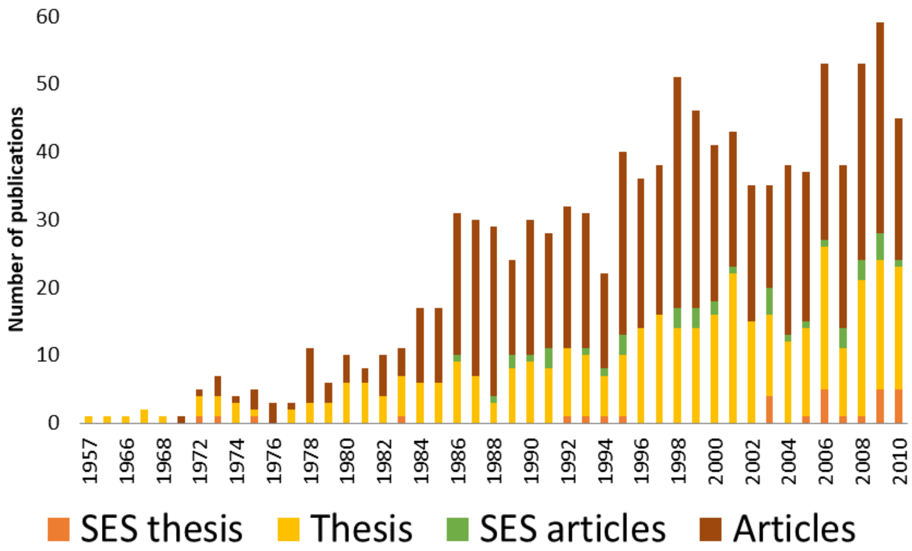


Figure 3. The number of publications in the Chamela-Cuixmala region. SES= social-ecological.

2.1 RESEARCH DESIGN AND METHODOLOGY

We addressed the different research questions through different approaches; for paper I, a theoretical approach was used to develop an analytical framework. For paper II, a methodological approach was used to develop a methodology that allows the integration and spatial identification of social and ecological data at the locally relevant decision-making scales previously identified in paper I. For paper III, we used an empirical approach to understand the quality of life (QoL) across the social-ecological system units (SESU) previously identified in paper II. An overview of the thesis research questions, papers, and approaches is presented in Figure 4 and Table 1.

The work presented in this dissertation is largely based on the already available indicators for the Chamela-Cuixmala region from previous research and publicly available data. The benefits of using this kind of data were two-fold: first, it allowed an exploration of the social-ecological dynamics at different local scales. Second, it allowed the development of new methods for operationalizing and integrating such different data in social-ecological analysis.

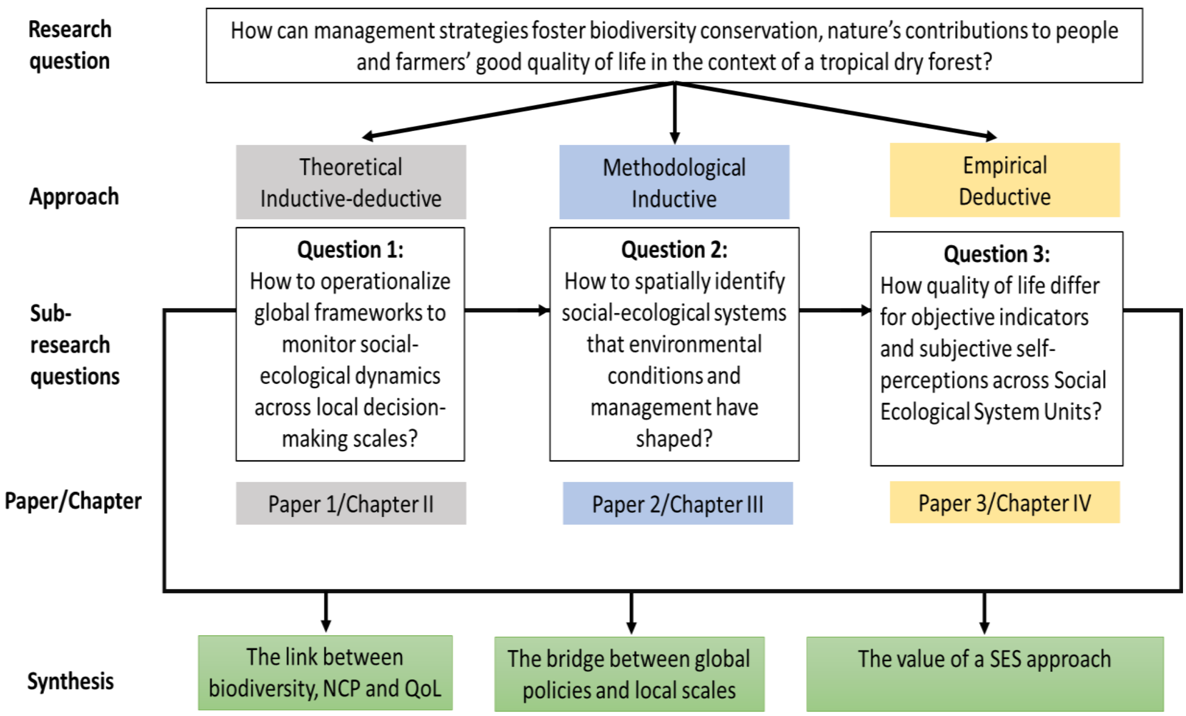


Figure 4. Overview of the main research question, approaches, sub-research questions, papers/chapters, and dissertation synthesis.

In **paper I**, the goal was to set an analytical framework that allowed the operationalization of global sustainability frameworks at local scales. Therefore, I conducted a literature review of all SES theses and articles in the Chamela-Cuixmala region and collected their available social-ecological indicators. These indicators were further categorized into the different components of the analytical framework proposed in an iterative deductive-inductive process that took seven iterative cycles. Once the analytical framework was constructed, I settled on the most relevant decision-making scales to operationalize the framework at local scales. I operationalized the framework by assessing how the different components and scales of the framework were represented by the local indicators of the Chamela-Cuixmala region.

Paper II aimed to develop a methodology to combine social and ecological data for local spatial identification of SES. We used the previously identified relevant decision-making scales from paper I as the scale of analysis. We implemented the proposed methodology by identifying social-ecological system units (SESU) in the Chamela-Cuixmala region through hierarchical clustering of collaborative databases on ecological and social-management information. We used publicly available data from the RAN (for its acronyms in Spanish Registro Agrario Nacional, Agrarian Nacional Registry) for the governance data. For the ecological data, we used the individual plots owned by *ejidatarios* (i.e., smallholders) as a unit of analysis; for the social-management data, the smallholders, and for governance data, the *ejidos* (further explanation about these scales is given in the next section of case of study).

In **paper III**, the goal was to assess how QoL differed from objective and subjective indicators across the different SESU previously identified in paper II. We used the data from 25 in-depth interviews previously collected in the Chamela-Cuixmala region. We analyzed the interviews through content analysis and developed a welfare index based on the most relevant variables mentioned by the respondents during the interviews (e.g., number of cattle, access to water, remittances. etc.). We compared the self-perceived material and no-material satisfaction with the welfare index and the items mentioned for QoL. A complete overview of the three papers, their methods, results, and main gaps addressed is given in Table 1.

Table 1. Overview of the three papers of my dissertation (P= paper)

Sub-research question	Paper	Methods	Main results	Addressed research gaps	Contribution
How to operationalize global frameworks to monitor social-ecological dynamics across local decision-making scales?	P1	Literature review	• Analytical framework with five components relevant for SES dynamics monitoring. • Analysis of Chamela-Cuixmala social-ecological indicators points to management and co-production as key components in the SES dynamics.	Gap1: feedbacks between social and ecological systems Gap 3: NCP co-production	Provide an analytical cross-scale framework to monitor SES dynamics based on the components of nature's contributions to people (NCP) that are relevant to assess social-ecological dynamics. Provide empirical evidence of the central role of co-production in the SES dynamics.
How to spatially identify social-ecological systems that environmental conditions and management have shaped?	P2	Hierarchical cluster analysis and comparative statistical tests	• Stepwise methodology to spatially identify locally relevant SES. • Typology of social-ecological system units (SESU) dynamics in Chamela-Cuixmala regarding land transformation, management intensity, and governance.	Gap1: feedbacks between social and ecological systems Gap2: Spatially identification of SES Gap 4: Effectiveness of governance systems	Provide a methodological approach to integrate different sources of indicators and map SES. Identification of topographical characteristics and public policies (PROCEDE) as key drivers in SESU delimitation Communal governance (communal land tenure) is associated with better biodiversity conservation.
How does the quality of life differ for objective indicators and subjective self-perceptions across Social-Ecological System Units?	P3	Content analysis and comparative statistical tests	• 48 Quality of life (QoL) items and dimensions were self-perceived. • More land transformation, more management intensity, and more individual governance were associated with a more current welfare index but a lower self-perceived satisfaction	Gap 4: Effectiveness of governance systems Gap 5: Contributions of NCP to QoL	SESU with more communal governance land tenure systems are associated with better self-perceived quality of life Provide empirical evidence that material NCP provision is insufficient for a good self-perceived quality of life.

2.2 CASE STUDY

Ecologically, the region is mainly composed of a mosaic of tropical dry forests (TDF) and grassland patches, but also of other ecosystems such as mangroves and wetlands (Figure 5). The topography is dominated by hills between 20-180 m, although some flatlands occur in floodplains and valleys along the main rivers and seasonal streams (Cotler and Ortega-Larrocea 2006). Rainfall is seasonal, with an annual mean of 800 mm, concentrated between June and October (Maass et al. 2018).

Socially, on the Jalisco coast, most people arrived in the area from different states of Mexico during the 1950s and 1970s during the Agrarian Repartition, which promoted the idea of fostering productive activities throughout the *ejidos*. *Ejidos* are one of Mexico's two types of communal land tenure systems. Land tenure within *ejidos* in this region can occur in three ways (Schroeder and Castillo 2013). First, *ejidatarios* (i.e., smallholders), or the landholding members of the *ejido*, can inherit the land right (*ejidal* plots), sell it, and vote in the *ejidal* assembly to take communal decisions. *Ejidatarios* have rights over communal lands within the *ejido*. Second, *posesionarios* possess land within the *ejido* but cannot pass it to the following generation. *Posesionarios* do not hold rights over communal lands and cannot vote in the *ejidal* assembly. Each *ejido* determines the level of *posesionarios* participation in collective management. Finally, *avecindados* have settled within the *ejido* for over a year, and neither possess land rights nor vote in the Assembly. Traditionally, men hold most of these three types of land rights and make land-related decisions, although there are few “*ejidatarias*” (women).

For over seven decades, *ejidatarios* have managed their lands under this communal scheme. *Ejidos* were formed through the Agrarian Land Reform to provide land to thousands of landless peasants after the 1910 Mexican Revolution. People on the Jalisco coast were promised to be allocated 15 to 35 ha per *ejidatario* for productive activities in their so-called *ejidal* plots (i.e., individual plots). In the Chamela-Cuixmala region, 70% of the remaining TDF outside the biosphere reserve is under this land tenure. TDF, however, was seen as a barrier to livestock and agricultural industries. As a result, the primary method of transforming TDF was clearing forests of all vegetation, burning leftovers to add nutrients to the soil, and then producing maize, beans, or sorghum (De Ita 1983). Then, non-native grasses were introduced, and cattle production started, lasting several years (Burgos and Maass 2004, Castillo et al. 2005). Even though the growth of agricultural activities completely altered forests, people considered this necessary. People today are proud of their productive systems, including developing communities with basic amenities and agricultural areas on plains or grasslands on hills. Despite this, communities face significant issues with access to clean water, sewage disposal, health care, education, and high migration rates to the United States (Castillo et al. 2005).

In this study, ejido, ejidatarios, and their individual plots are the focal units of analysis because they represent the region's most important spatial planning and decision-making units for governance.

Figure 5. Exemplary landscapes dominated by mosaics of tropical dry forests and grasslands in the Chamela-Cuixmala region. Photos taken by the author

2.3 RESEARCHER POSITIONALITY

I do not want to end this methodological section without reflecting on my position and role as a researcher in this process. In some of my lectures at the beginning of the PhD, we saw the theory proposed by Donna Haraway (1991) concerning the partiality of the researcher and how knowledge is constantly contextual. My experience as a young, highly educated female researcher in elderly rural communities with heavily masculinized activities has significantly impacted this research because I wanted to have the "hero(ine)" role (Chambers et al. 2022). I assumed that something "useful" for the smallholders could be an outcoming of my thesis.

Despite my desire to make this research as transdisciplinary as possible, this research is on the threshold between positivist research, research that considers people and nature as objects of study or a source of information and that conceives itself as the expert and the possessor of the knowledge (Park 2006), and a qualitative research approach. In the qualitative research approach, the social actors, settings, or groups are seen as a whole and not as mere variables. Through this approach, social perceptions are documented, as well as the motives and intentions of people to understand and interpret their vision of reality and actions (Hernández et al. 2006, Romo-Díaz 2017). In these perspectives, preconceived hypotheses or theories are not evaluated but instead seek to obtain depth in the data collected and the contextualization of the environment through the study of and with the actors in their environment. Data analysis is a continuous and cyclical process. This dissertation does not have preconceived hypotheses, and the construction of knowledge occurred in a cyclical process; however, the structuring and general positioning of the thesis is more of a positivist nature.

Despite the methodological approaches I have used, I want to state that I stand for science as a facilitation tool that fosters dialogue and creates enabling conditions for social learning (Wittmayer and Schäpke 2014).

3. KEY FINDINGS

The main results of each paper/aim are briefly outlined in the following sections.

3.1 RESEARCH AIM 1: ANALYTICAL FRAMEWORK TO OPERATIONALIZE GLOBAL FRAMEWORKS AT LOCAL SCALES

This aim corresponded to **paper I** (chapter II of this dissertation), where we have operationalized the IPBES and Essential Ecosystem Services Variables (EESV) frameworks at local scales through an inductive-deductive process. We have identified five distinct components of the social-ecological system's dynamics important to monitor NCP at different local decision-making scales: *Co-production, management, ecological supply, demand, use and values*, and *benefits from NCP* (Figure 6A). Additionally, we identified three decision-making scales relevant for the monitoring at local scales: tenure unit, smallholder, and individual plot. We proposed a series of sub-components for each component for its monitoring (Figure 6B). Then, we assessed this framework components, subcomponents, and scales in indicator from our case study (Figure 7), where they evidenced three main aspects: 1) *management* and *co-production* played an important role in the SES dynamic because they were highly monitored and evenly monitored at the three different scales; 2) there is no agreement on the indicators for the *NCP co-production* at the different scales, which makes it difficult to make comparable results across study cases; and 3) the framework that we proposed was functional and integrative to operationalize global frameworks at local scales to monitor social-ecological dynamics.

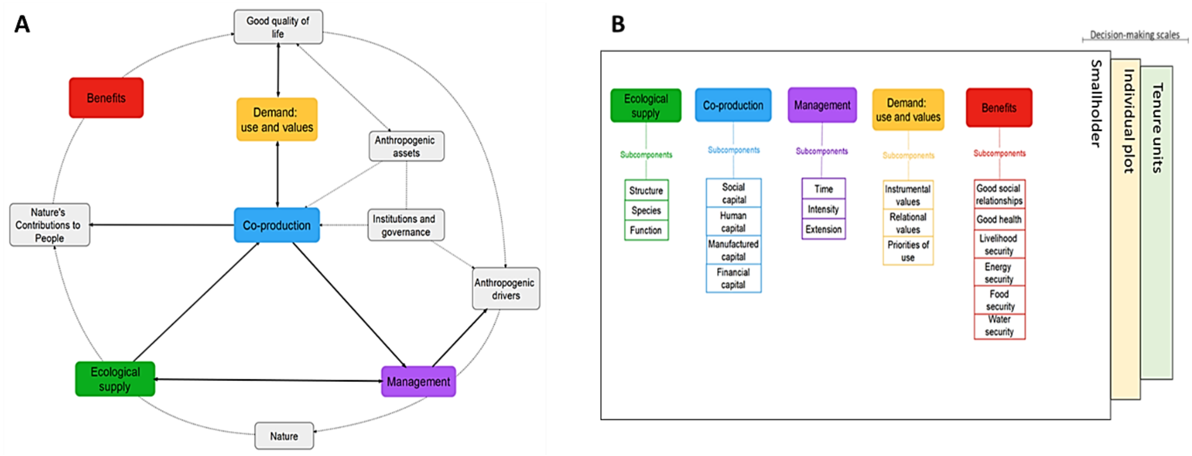


Figure 6. Main results from paper I to operationalize IPBES and EESV frameworks at local scales. (A) Analytical framework to monitor NCP. (B) Decision-making scales to operationalize the analytical framework and the subcomponents for the monitoring.

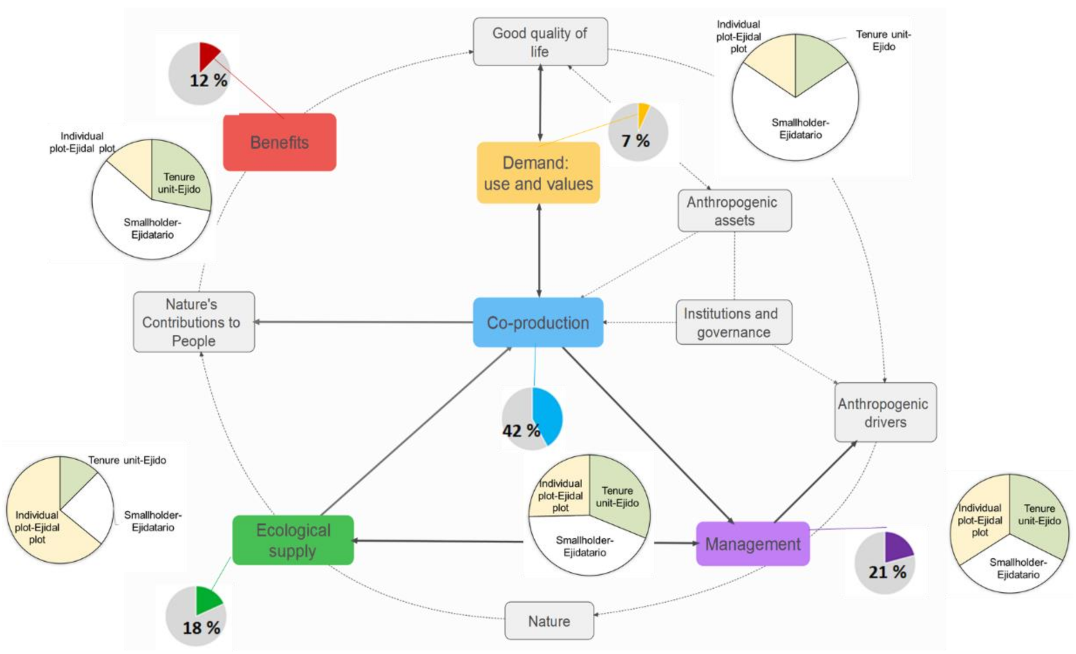


Figure 7. Assessment of indicators in the Chamela-Cuixmala region per component and scale. Co-production and Management components stand out for their higher monitoring in the area and even monitoring across the three decision-making scales.

3.2 RESEARCH AIM 2: SPATIAL IDENTIFICATION OF SOCIAL-ECOLOGICAL SYSTEM UNITS (SESU)

This aim corresponded to **paper II** (chapter III of this dissertation), where we have provided a methodology to identify social-ecological system units (SESU) at the finest local spatial scale (Figure 8). The methodology consisted of three steps, first, to identify ecological clusters at the individual plot scale spatially; second, to identify clusters of plot owners based on the social-management data; and third, to spatially identify the SESU at the minimum governance unit and describe these units by their ecological and social-management clusters associated (Figure 8). This methodology is especially relevant, where social-ecological data is collected at different scales. By this methodology, the SESU maps obtained can create spaces for dialogue with stakeholders about sustainable management options at the finest local governance scales.

We applied this methodology in our case study and found four ecological, social-management, and SESU clusters. Differences between ecological clusters were based on their elevation and land cover type. The social-management clusters differed according to the management intensity of cattle and forests. Differences between SESU were based on land management regime (individual vs. collective tenure), plot sizes, and time under private schemes. The SESU identification revealed a geographical gradient from the country's center (SESU1) towards the coast (SESU4). Moreover, the different SESU represented a gradient of land cover transformation (from SESU1, the least transformed, to SESU4, the most transformed), management intensity (from SESU2, which is the most extensively managed to SESU4 that is the most intensively managed), and governance systems (from SESU1 that mostly implemented communal governance to SESU4, which governance system mostly rely on private land and individual land tenure) (Figure 9).

We used the resulting SESU map (see complete results in chapter III) together with the results of former research in the area to conduct an outreach tour in June of 2022 (see Appendix 2 and 3 for the outreach tour material and pictures) to discuss with the smallholders these results as well as their wishes for future research in the area.

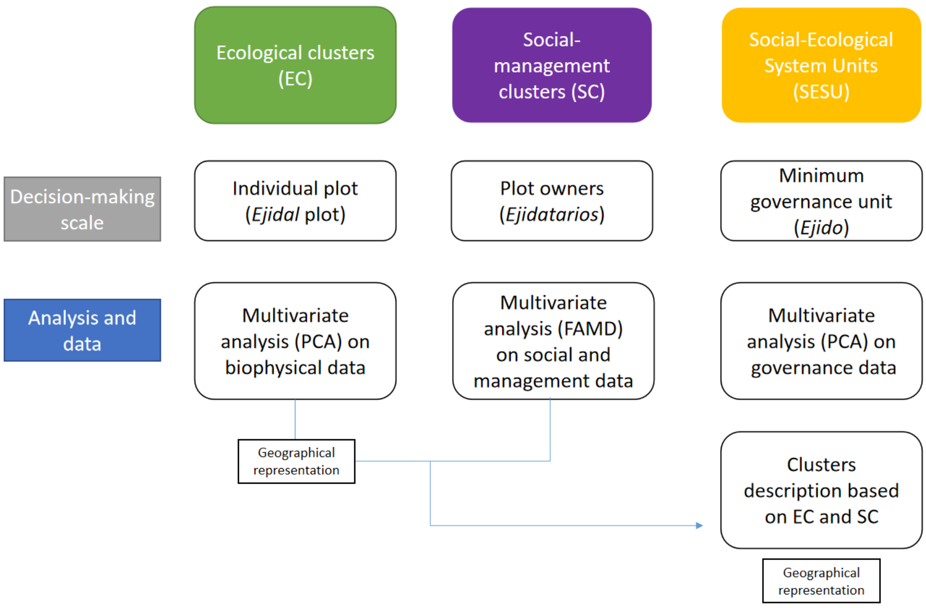


Figure 8. The methodological approach proposed to identify the Social-Ecological Systems Units (SESU) spatially. PCA=Principal Component Analysis. FAMD= Factorial Analysis of Mixed Data.

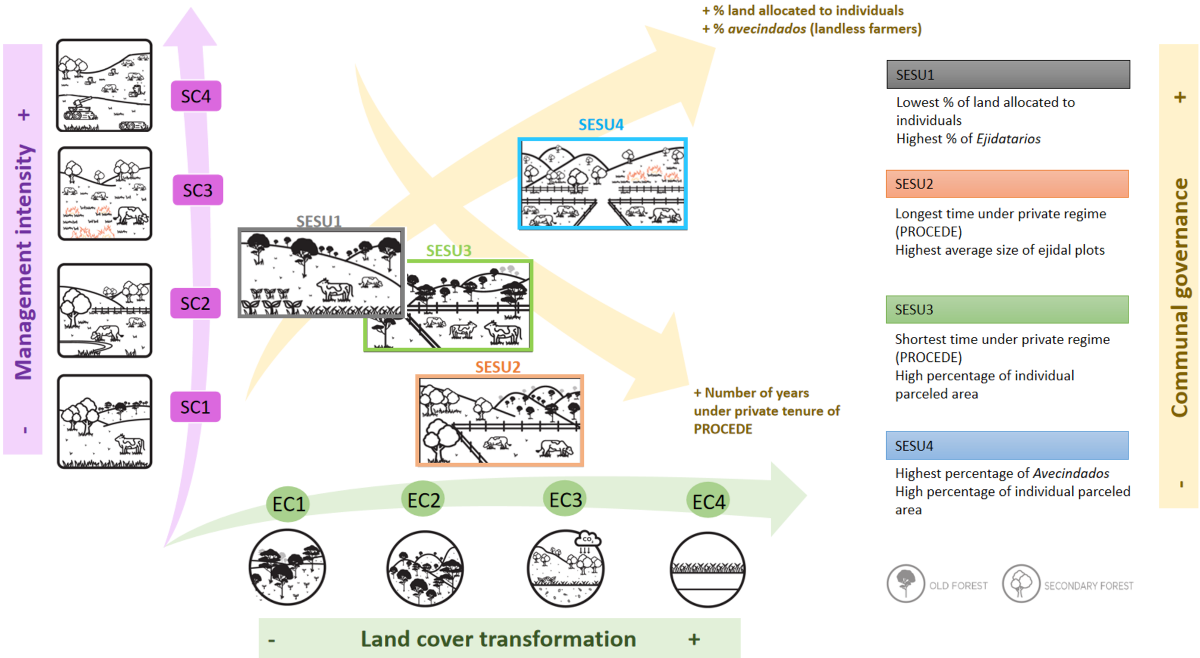


Figure 9. SESU association regarding the highest percentage of Ecological clusters (EC) and Social-management clusters (SC). Right boxes represent the SESU description regarding governance variables.

3.3 RESEARCH AIM 3: SESU INFLUENCE ON SMALLHOLDER'S QUALITY OF LIFE

This aim corresponded to **paper III** (chapter IV of this dissertation), where we have empirically assessed the smallholder's quality of life for both the subjective and objective approaches across the SESU previously identified in paper II. We first looked for all the quality of life dimensions where we found a wide diversity of QoL perceptions revealed in the 48 QoL items belonging to six categories: 1) Social capital, 2) Nature, 3) Economic capital, 4) Pleasant non-work activities, 5) Agency, and 6) Government and services, and two additional dimensions referred to obstacles and enablers of QoL. Secondly, we found that the social and economic capital were relevant for the four SESU. The SESU with the highest land transformation (SESU4) perceived more enablers and obstacles of QoL (Figure 10). Finally, we found that as management is intensified and governance fosters individualism across SES (i.e., individual land tenure in SESU4), the higher the Current Welfare Index (Figure 11A) and the lower the self-perceived material and non-material satisfaction (Figure 11B).

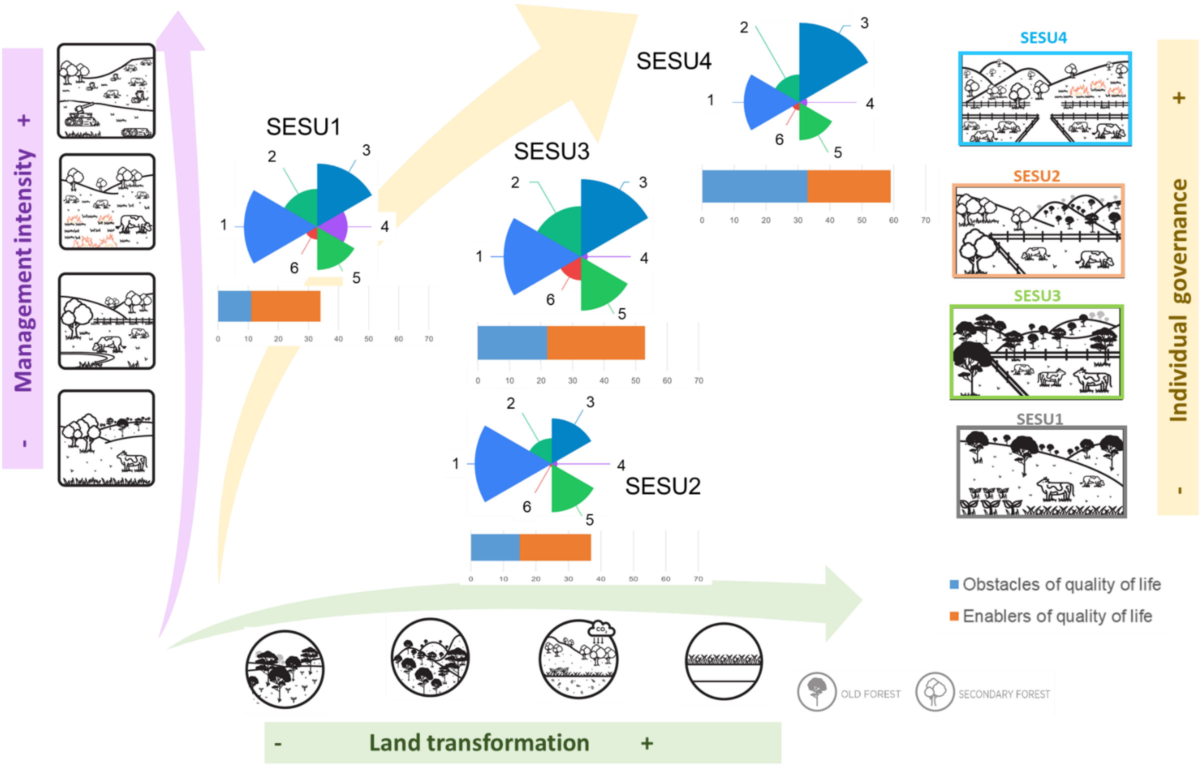


Figure 10. Current dimensions of QoL perceived across SESU. 1. Social capital. 2. Nature. 3. Economic capital. 4. Pleasant non-work activities. 5. Agency. 6. Government and services. The SESU are shown in an increasing gradient of land transformation (SESU1, SESU2, SESU3, and SESU4), management intensity (SESU2, SESU3, SESU1, and SESU4), and individual governance (SESU1, SESU3, SESU2, and SESU4).

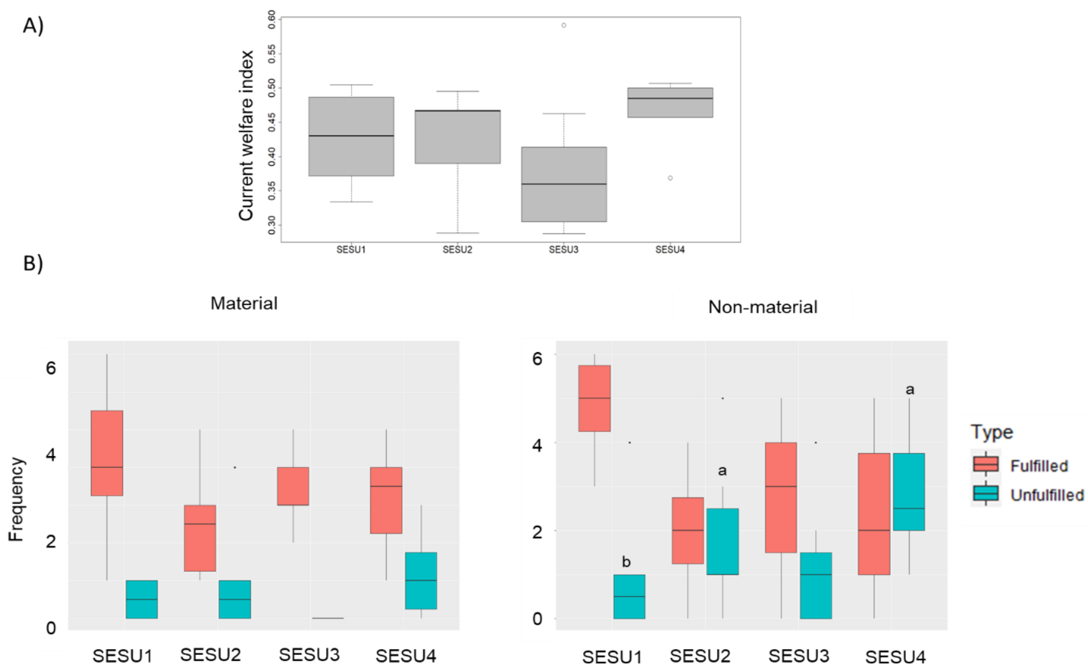


Figure 11. Objective and subjective approaches for QoL fulfillment across SESU. (A) Current welfare index differences among four SESU. (B) Material and non-material fulfillment or unfulfillment among four SESU. Lowercase letters indicate significant differences between SESU (Tukey posthoc test, p-value < 0.05).

4. SYNTHESIS

This thesis explores the links between biodiversity, NCP, and QoL within the social-ecological systems framework. The key contributions of each paper can be summarized as follows:

Paper 1 provides an analytical cross-scale framework to monitor SES dynamics based on the components of NCP that are relevant to assess social-ecological dynamics and provide empirical evidence of the central role of co-production in SES dynamics.

Paper 2 provides a methodological way to integrate different sources of indicators and map SES. It identifies topographical characteristics and public policies (PROCEDE[1]) as key drivers in SESU delimitation and the association of communal governance (communal land tenure) with better biodiversity conservation.

Paper 3 identifies the association of communal governance land tenure system with better self-perceived quality of life and provides empirical evidence that material NCP provision is insufficient for a good self-perceived quality of life.

I briefly discuss these contributions and several cross-cutting insights and reflections in the next sections.

4.1 THE LINK BETWEEN BIODIVERSITY, NCP, AND QOL: THE ROLE OF MANAGEMENT AND GOVERNANCE SYSTEMS, CO-PRODUCTION, AND VALUES UNDERPINNED BY PUBLIC POLICIES.

Overall the findings of **paper I, paper II,** and **paper III** showed that the links between biodiversity (with the proxy of forest land cover), NCP provision (with the proxy of cattle raising), and QoL is deeply rooted in the type of governance expressed by the land tenure and by the management and co-production associated, as well as to the values underpinned by public policies. **Paper II** showed that communal governance (expressed through the communal land tenure of *ejidatarios*) is associated with better biodiversity conservation. Moreover, **paper III** showed that this communal land tenure is associated with more self-perceived satisfaction of QoL. **Paper III** also provided empirical evidence that material NCP provision (proxy with the number of cattle) is insufficient for a good self-perceived QoL. In the following, I discuss the role of governance systems in terms of land tenure different types and their management associated; the co-production, and the values underpinned by public policies in fostering a good quality of life.

Management is a key component in the SES dynamics often addressed at the local scales research (Zermeño-Hernández et al. 2015, Trilleras et al. 2015, Pérez-Cárdenas et al. 2021). **Paper I** advances global frameworks by acknowledging management's key role in the SES dynamics at the local scale. Furthermore, regarding the management type, governance type has also been signaled as an important factor to consider in land management strategies (Neyret et al. 2023). Communal governance, most commonly referred to as “customary governance,” is where the communities are at the center of the decision-making processes (Mainville 2021) and has proved to have better ways of managing biodiversity. Although there is controversy over this subject (Bonilla-Moheno et al. 2013), some examples exist of how communal governance is better for biodiversity. For instance, this includes the management of *ejidal* forests where the ocellated turkey lives in Campeche (Mexico), the

[1] Program for Certification of *Ejido* Rights and Titling of Urban Plots

communal areas protected in forests of Oaxaca (Mexico) (Carabias et al. 2010), the protected areas in Chile managed by indigenous people in communal ways (Huaiquimilla-Guerrero et al. 2022), and the autonomous indigenous communities in Colombia that are self-organized (Velasco 2012). Hayes and Murtinho (2018) found that community-organized households receive benefits and perceive fair distribution of ecosystem services more efficiently, while less organized communities lack budgetary information or agreement. In fact, in **paper II** we confirm that when we accounted for the type of governance (proxy with the type of land tenure) and the management intensity. We found that communal land tenures (i.e. *ejidatarios*) are associated with lower management intensity rates, while private land tenures (i.e. *avecindados*) are associated with a higher management intensity. **Paper III**, confirms that management intensities are associated with different levels of self-perceived QoL satisfaction. Smallholders were more satisfied in communal land tenures while they were less satisfied in more private land tenures. It should be noted that these results are for the communities that I analyzed and results cannot simply be generalised to other contexts. However, all this together suggests that global policy-makers and researchers must pay greater attention to, and support, the governance capacities of communities to foster better management strategies that can conserve biodiversity while producing people's good QoL.

The co-production of NCP was proved to be also a key component in the SES dynamics in **paper I**. In fact, in **paper I,** we acknowledge this central role, and we place the anthropogenic assets in the form of the capitals proposed by Palomo et al. (2016) in the co-production component, which is an advancement to the IPBES framework that acknowledges the central role of these assets but does not propose an analytical framework to monitor them. Anthropogenic assets are part of the key drivers that underpin management decisions in the Chamela-Cuixmala region. **Paper II** advances to understand how access to these assets, such as financial and material capital, affects management decisions. For instance, we have proved that the size of the individual plot influenced the type of management. Bigger plots had less intense management, and vice versa; smaller plots had more intense management because farmers on bigger plots had fewer resources to invest in such bigger areas. Similar results have been found in communal forest land tenure in China that has been parcellated recently (Xie et al. 2014); they found that households have a limited amount of capital to invest in forest management and that because of this constraint, parcelization of forestland resulted from the recent reform in China has not yet caused any change on the intensity of investment in forest management. In **paper III,** we have proved how financial and human capitals are relevant for the current and desirable QoL of smallholders in the Chamela-Cuixmala region. These capitals have also been important in other examples (Fagerholm et al. 2020). However, in **paper III**, we also have found through the current welfare index that more anthropogenic assets, particularly material assets, do not mean a better self-perceived QoL, proving the environmental paradox true for rural areas (Raudsepp-Hearne et al. 2010). The central role of the anthropogenic assets in the co-production of NCP has led to adaptative management in the Chamela-Cuixmala region. Through the Chamela-Cuixmala case study, we can learn how global policies would benefit from considering these assets to foster more sustainable management practices.

The values of productivity and modernization underpinned by public policies through the development model promoted by the Mexican government during the 50s fostered intensive agriculture and cattle farming at the cost of the TDF transformation (Castillo et al. 2005). In this sense, our findings highlight the utility of the new typology of values recently issued by IPBES (2022). This report aims to inform policymakers to determine how best to deal with different types of values of nature in different decision-making contexts. This IPBES new value typology delimits three value domains. First, worldviews describe how people conceive and interact with the world. The next domain in the typology is broad values, which encompass guiding principles and life goals. The third domain is specific values, which refer to judgments regarding the importance of nature in particular contexts. Additionally, these three value domains can be framed by people in different relationships with nature, or life frames, such as living from nature, living in nature, living with nature, and living as nature. **Paper III** suggests that when public policies foster values of prosperity and subsistence through values such as "living from" nature, aspirations to want to have more material aspirations are generated. When the biophysical conditions are not met to satisfy these aspirations of smallholders, thus other types of values have been fostered in its inhabitants, such as "living with" nature, through stewardship and responsibility, as well as specific values of people with their environment.

4.2 THE BRIDGE BETWEEN GLOBAL POLICIES AND LOCAL SCALES

Global targets such as sustainability and QoL are best addressed through multi-level governance (Berkes 2007). Integrating local perspectives into global scale frameworks can facilitate the development of metrics more appropriate for in situ communities and support the innovative approaches to research-based policy and action necessary to confront complex environmental challenges (Sterling et al. 2017). Previous social-ecological exercises to foster monitoring at local scales have identified a set of relevant variables at the local scales (Ostrom 2009, Frey 2017, Sterling et al. 2017, Pacheco-Romero et al. 2020). However, there is a latent need for a dialogue between global and local scales in the monitoring and policy interphases. **Paper I** addresses this need by providing an analytical cross-scale framework that contributes to the transferability of the global integration of the temporal, spatial, and governance scale mismatches of place-based research (Balvanera et al. 2017). Global efforts could also explicitly consider the standardization of indicators based on local information. Indicators capturing information in the same way regardless of local context may not be meaningful (Sterling et al. 2017). Conversely, indicators developed on local scales and reflecting specific place-based values may be easier translated to other scales or national and international policy by applying the framework developed in **paper I**.

To monitor and evaluate sustainability effectively, we need mechanisms that allow for translation between place-based contexts and other scales, including local and regional governance layers. In **paper II,** we provide a methodological way to integrate different sources of indicators and map SES. Through the iterative process of **paper I** and the application of the methodology of **paper II** in our case study, co-production and management came up as very relevant components to tackle the scale mismatch challenge in the SES research (Cumming et al. 2006). We also identified the topographical characteristics and anthropogenic assets as key drivers in SES delimitation.

There are examples of how topography can determine land use patterns and forest cover distribution, particularly in tropical regions (Freitas et al. 2010) and in temperate cultural landscapes (Hanspach et al. 2016). Regarding soil dynamics, Zhang et al. (2021) found that in woodland areas, soil respiration increases in flat areas while it decreases in slope areas. Carbon to nitrogen ratio and soil density also varied with topography, with larger slope changes than flat topography. However, we found the opposite in **paper II**, where we found that in flatter areas, soil density was higher, with less organic carbon showing the level of degradation of the flatter areas mostly used for agricultural and cattle activities. Therefore, from **paper II,** we conclude that topography underpins the management decisions in the area and is a key driver to consider when tailoring specific strategies for the management of TDF at the local scale.

In **paper III**, we tested how land management strategies materialize the QoL in the region. We found different visions associated with the management, on the one hand, smallholders with a vision of stewardship of the land and overall satisfaction with their life, and on the other hand, smallholders whose visions were to have more cattle and accumulate richness with an overall dissatisfaction of their life. A vision more aligned with the neoliberal progress imposed in the area through public policies (Schroeder and Castillo 2013). Cattle ranchers of the Chamela-Cuixmala region are vulnerable; for decades, they have been experiencing family fragmentation due to migration to the USA or to the states nearby (INEGI 2023) due to insecurity, loss of land fertility, hurricanes, and in general, the lack of opportunities. These changes derived from other key changes, such as the signing of TLC (for its Spanish acronym *Tratado de Libre Comercio* or NAFTA in English, Toledo 1996) and the formalization of PROCEDE [2] policies that are weakening the countryside. To alleviate this, it is crucial to implement

[2] Program for Certification of *Ejido* Rights and Titling of Urban Plots

policies that balance economic development and foster values more aligned with protecting NCP to QoL (Chan et al. 2016, Deng et al. 2016, IPBES 2018).

4.3 THE VALUE OF A SES APPROACH. WHAT IS IT FOR THE SMALLHOLDERS IN THE CHAMELA-CUIXMALA REGION?

The social-ecological systems approach provides useful lenses for examining complex issues, encouraging cross-disciplinary collaboration, and advocating for resilient and sustainable practices in the face of major global issues like biodiversity loss and social-ecological transformations. One of the key approaches in SES is place-based research that addresses the particularities of specific landscapes. In fact, for this thesis, I have relied on a large data set from a collaborative process in the Long Term Social-Ecological Research network, which the Chamela-Cuixmala region is part of. The relevance of the long-term monitoring networks is key in ecological and social processes to produce knowledge relevant to building resilience and halting land degradation and biodiversity loss (Mastrángelo et al. 2019). As we have proved in **paper I**, place-based research allows a better understanding of global social-ecological dynamics. Place-based social-ecological research is also uniquely positioned to explore the interplay between the local and the global scales by recognizing the distinctiveness of local entities, as we did in **paper III** while addressing the impacts of global dynamics from them (Balvanera et al. 2017). Through our example in this dissertation, we agreed that intense collaboration is urgently needed within the community of scientists and practitioners. The construction of Communities of Practice at different scales, in which local communities, practitioners, decision-makers, and researchers share expertise and visions to co-produce relevant knowledge and to nurture governance systems that can significantly contribute to mobilizing sustainability expertise across scales (Balvanera et al. 2017). At the beginning of this thesis, a big endeavor and concern were what would be our contributions to the smallholders in the Chamela-Cuixmala region. In the end, we have mobilized the findings of **paper II** of this dissertation and results from other research previously made in the area through a poster (Appendix 2) that we presented during an outreach tour in June 2022. During that tour, we visited the nine *ejidos* surrounding the biosphere reserve; we held three focus groups and 15 face-to-face talks to dialogue about such findings and the concerns and needs of the people. Discussions raised issues such as how to enhance the relationships between Academia and the smallholders.

5. CONCLUSIONS AND FUTURE RESEARCH AVENUES

Exploring the connections between society and ecosystems requires incorporating multiple scientific perspectives. The social-ecological systems approach has allowed me to do that in this dissertation; from the theoretical approach in **paper I** to the methodological approach in **paper II** up to the empirical approach in **paper III,** this dissertation has contributed towards building a better understanding of the transferability to the global integration of the place-based research and the spatial patterns of SES identification and how the landscape configuration is associated to the QoL of the smallholders.

Theoretically, this dissertation gained an understanding of the SES dynamics and informed sustainability from a Global South place-based case study. Methodologically, our place-based case study advanced in understanding the local scale mismatch and the SES dynamics. Empirically, this dissertation addresses how landscape configuration shapes the perceptions of smallholders' QoL; furthermore, we provide evidence of the environmental paradox in rural contexts and show how governance based on communal land tenure is associated with higher QoL fulfillment. This knowledge is essential to inform management practices that can sustain NCP's availability and foster the people's good QoL. Therefore, I would like to answer the main research question of this dissertation in this section: How can management strategies foster biodiversity conservation, nature´s contributions to people, and farmers' good quality of life in the context of a tropical dry forest? In the given context of the Chamela-Cuixmala region, it is clear that the straight answer is fostering communal governance organization, visions, and values that go beyond the neoliberal imposed progress through public policies. In **papers II** and **III**, we proved that cattle could live along with the forest through a vision of stewardship of nature as the classical vision of "*campesinos*" (farmers) (Bartra 2002).

While best practices have been widely developed for community-based governance approaches, new theories and methods are needed to link local goals with sustainable management outcomes critical to global policy objectives (Sterling et al. 2017). In particular, I envision four main areas that can be further developed from this dissertation.

First, this includes the detrimental contributions from NCP and relational values. The NCP paradigm also considers the detrimental contributions of nature to people (Díaz et al. 2018). Future research can apply the framework proposed in **paper I** to assess beneficial and detrimental contributions, how they impact people's quality of life, potential conflicts between stakeholders, or who are the winners and losers. The framework's application can be extended to include undesirable relational values (Hoelle et al. 2022) to measure the efficacy of management techniques to improve the sustainable flow of beneficial NCP while minimizing natural impairments and potential stakeholder conflicts.

Second, my work touches on a broader subject in which interdisciplinary work is needed. That is the gap concerning the role of power relationships that from this dissertation is two-folded; first, **in paper I**, I identify the mediating role of the co-production and management through the different access to the anthropogenic assets, and second, **in paper II**, through the exerted power across governance scales. Power relations affect how stakeholders can access and use NCP (Chaudhary et al. 2018) or access and use the capitals supporting NCP co-production (Vallet et al. 2019), as well as by determining who can participate in NCP management (Felipe-Lucia et al. 2015, Berbés-Blázquez et al. 2016). Despite the relevance of power relations mediating social-ecological dynamics (e.g., Vallet et al. 2019, Martín-López et al. 2019), there is still a gap in the need to study how power operates, shaping the NCP supply, demand, and governance to lever sustainability.

Third, consider more anthropological studies in the Chamela-Cuixmala region to understand processes of migration, insecurity, and palliative measures from the government. To my knowledge, there are no recent studies from the political ecology or ecological economics that make a critic of the social policies and rural policies in the Chamela-Cuixmala region.

Finally, by doing this work, I found that art is a way out of the crisis. Therefore I identify that we scientists need to share and discuss the results with the smallholders through art-based approaches. A key gap in research is sharing the results with smallholders through horizontal dialogues (Bubela et al. 2009, de la Vega-Leinert and Schönenberg 2020). Furthermore, a more flexible approach with art-based methods is conceivable to enhance human-nature connectedness. The emotions and embodied experiences that science frequently ignores can be tapped through arts-based approaches. Due to the non-verbal nature of most art forms, using them in the research process may go beyond the cognitive to elicit tacit information. It also qualifies arts-based research for fostering emotional ties to nature (Muhr 2020). At the same time, art can be an empowerment element of expression for marginalized people or those who feel oppressed and excluded (Bode Bakker and Nuijten 2018). It can be a way to imagine a utopian world and launch dissatisfaction; that can also be the start of a utopia. A world that can imagine its future is a world that might have one.

6. REFLECTIONS ON MY RESEARCH APPROACH AND MY RESEARCH PATH

In this section, I want to share my reflections on conducting an interdisciplinary PhD; what brought me here (my academic path), some (emotional) constraints along this PhD pathway, how I transformed some of my assumptions, and how I faced the vicissitudes, for instance, the pandemic that passed all us through. They are not specifically in this order but instead intertwined in a series of reflections and a story, my story.

As I stated before in the preface, early in my career, I assumed the “Hero” posture as a scientist by thinking, “ok, Nature is dying, I will do something. We have to act NOW!” and I started investigating restoration ecology, with a lot of very quantitative analysis and models. I even went further in my statistical analysis education. However, when I started working with farmers and finding ways to make agriculture more sustainable, I realized that “numbers” were insufficient. That we needed to work together. I moved my focus to research agroecological and agroforestry techniques, which is how I started my PhD. Thinking that with my modeling competencies, we could work with smallholders to find convenient management strategies for them and Nature, similar to Neyret et al. (2023). During my last master's thesis, I promised myself I would not do positivistic science again; I wanted to work with people in a more transdisciplinary way. However, that is not a straightforward endeavor, so here we are from a positivistic approach, providing meaningful insights for sustainability. Now, I will tell you briefly some reflections that arose during these five years of PhD.

During the first semester of this thesis, I was part of a seminar in Mexico that was intended to be as transdisciplinary as possible. We worked in a watershed called Umécuaro in Michoacán, Mexico, trying to understand their problems. Coming from the natural sciences, I was used to “asking data to nature.” To collect data. However, everything changed when instead of data, I was collecting stories. How can you listen to heart-breaking stories about people losing their land because of illegal land lodging, avocado expansion, or pollution and remain without doing anything? Without feeling rage, anger, and deep sadness.

Moreover, who was I angry at? The lodgers for being “bad” persons? At the US companies coming to Mexico and placing their greenhouses full of chemical supplies? Or the consumers for eating avocado non-sense? I was not even able to identify THE problem because there were many, and they were all intertwined.

My classmates and I were really depressed by listening to all the stories in this transdisciplinary project. Then a professor told us, “Our obligation as scientists are to look for alternatives, even in the most challenging circumstances.” Therefore, I keep standing still, crossing boundaries. Mental boundaries on how research can be done, crossing disciplinary boundaries and trying to build bridges among them, for instance, during my first paper, in which the interdisciplinary deductive-inductive process took almost two years and a half. Finally, I (we) developed an analytical framework that researchers can use in the future (I hope).

I crossed spatial and cultural boundaries by studying abroad in Germany. Coming from Mexico, I faced the challenge of crossing the boundary of decolonizing my mind, my research, and even my soul. I tried to avoid as much as possible the parachute science (Asase et al. 2022), I had one co-supervisor that has been deeply involved in the Chamela-Cuixmala region for more than a decade, and I worked closely with the researchers working in the region, for instance for the papers two and three.

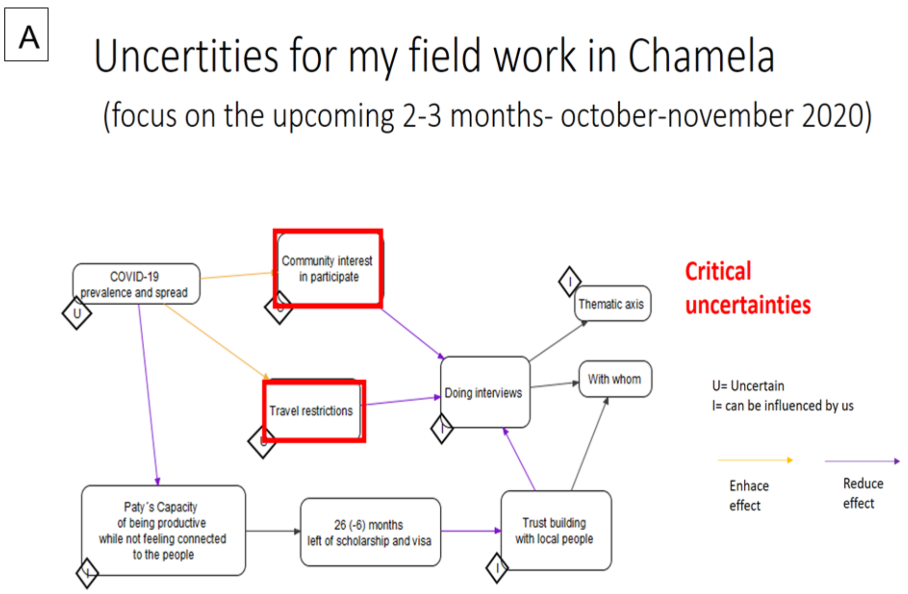
However, once on the field, what do you do when people tell you, *Ok, we will listen to you but fight with us, asking for support from the government*. Now I know that there is a name for that, and it is the awareness of power relationships. The awareness that there is no such thing as being neutral and that as scientists, we have a privileged position, yet a conflicting one. I moved from wanting to be a “superhero” to trying to be a “woodpecker,” and then to foster the “host” in me to listen to all the different voices, and finally accepting that I have a “genie” that wants to feel useful (Chambers et al. 2022). Where did it come to me that belief that I could do something or even “save” others? I felt pretentious, and I think it comes from privilege.

I had come to a moment with so many doubts, questioning if I was crazy or too stubborn to keep wanting to have something useful out of my thesis (other than papers). Validating myself was a boundary in itself. I see that many of us, sustainability researchers-students, are struggling with the feeling of doing something useful to save the biodiversity and the people. Maybe transformation is not about saving lives and changing the whole food system in my case study but getting together scientists with different perspectives and fostering dialogues and negotiations. Something that I managed to do at the end of my outreach tour, where I held a workshop with students and researchers working in the Chamela-Cuixmala region to discuss how we want to continue doing research in the Chamela-Cuixmala region. What is missing? What can we do better? The report of that workshop is in Appendix 4, in Spanish.

In the middle of this PhD, I realized how much fear I had to take that step in doing things differently and taking my own decisions for my project all by myself. I realized too, how many boundaries I have crossed. I learned the diplomacy needed to say uncomfortable things. As Donna Haraway says, I learned to accept the discomfort and navigate with that. I have also realized that it is also about being OK with others' discomfort, that "we have to give ourselves the right to not just observe" (Julia Steinberg).

However, sometimes as scientists, we cannot choose our role because we are pushed to some corner, and then it is important to remind ourselves that "a political strategy does not have to be our political home" (Adrienne Maree Brown). The COVID-19 pandemic came to change our life and projects in a crashing way. Regarding this PhD project, this pandemic entailed canceling fieldwork in 2020 and 2021. This fact severely affected my motivation for the project. It reinforced in me the importance of connecting with local stakeholders through participatory approaches for the PhD, given that they were the most vulnerable populations to face the virus. Not only was my project threatened by this situation, but also my professional performance and mental health in the context of risk infection in a foreign country.

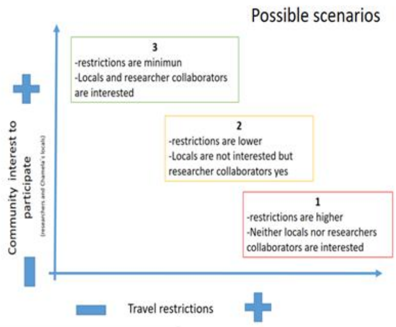
The strategy assumed to face the Covid-19 pandemic for my thesis was to follow the scenario analysis methodology proposed by Dr. Jan Hanspach (www.bioculturaldiversity.de/scenarios-covid-19-pandemic/). I identified the critical uncertainties for my project, where anyone could not have any influence, including the travel restrictions and local actors' interest in participating in the interviews (Figure 12A). With these two critical uncertainties, I created three possible scenarios in a gradient for each. With my supervisors, we decided to move forward in the project within mind scenario 2 (Figure 12B); that is, no workshops or interviews will be held. Instead, we would create an art-based product for the local actors with the results that I would hold by the end of 2021 with maybe some participation of *ejidatarios* (smallholders) that can have access (and willingness) to do online communication.



B

Risks per scenario and how to deal with them

(In the upcoming 4 to 10 months-december 2020-July 2021)



To January 2021	Risks	Possibilities to cope with it for paper 2	Possibilities to cope with it for paper 4
Scenario 1 Covid ongoing and no interest	No possibility of doing fieldwork or interact with the local people. Researchers to busy to send their data.	Work with Patty´s lab data for the typology	Rely on the trust builded of past students and the capacity to contact ejidatarios. Change the 4th paper to an art based product to Ejidatarios
Scenario 2 Still covid but researchers interest	No presencial workshops or interviews. No integration of ejidatarios voices for the modelling	Do a zoom workshop with researchers to collect data	Do a zoom workshop to join research and art in one product
Scenario 3 No covid and people interest	Paty would need to have the workshop ready by May 2021. To do the interviews.	Stay as planned, readjust gantt chart. No research stays.	Stay as planned, readjust gantt chart. No research stays.

Figure 12. Scenario planning to face pandemic Covid-19 in this research project. A) Identification of critical uncertainties for the project. B) Coping strategies per possible scenarios.

The covid-19 pandemic and the chronic illnesses of two close persons pushed me to an introspective work and find new ways of approaching complex sustainability issues. I came up with the idea and necessity of including more senses through art, for instance, music. To “Sentipensar” a word in Spanish that means feeling and thinking simultaneously. To work together with science and art. Senses and thoughts. Although I could not do an art-based product, fortunately, in June 2022, I was able to do an outreach tour through the nine *ejidos* I have been working only via their virtual data to give them back the results and to have focus group discussions and interviews to dialogue about them. This tour was, for me, the biggest accomplishment of this thesis because I could mobilize the social-ecological information with my idealized smallholders and better integrate and understand their feelings and emotions towards their work, the Academia, and the relationship between these two. At the same time, this outreach tour was the biggest existential crisis of my PhD. My inner hero(ine) scientific role was deeply disappointed. I was not expecting to have such an indifferent response from the smallholders. It took me a while, and to have deep conversations with my peers, to understand that knit webs of trust take so much time and effort and that the power relationships in the Academia-stakeholder dynamics that exist in the area are not something that I can change in two weeks that I am visiting. I learned to validate my energy and hunger to do science differently, horizontally, transformative, and transdisciplinary. I learned those processes take long construction pathways of trust, patience, compromise, and reliability. Much reliability. For that, I am thankful and at peace with this PhD.

During my PhD, I also faced contrasting values around cattle raising. On the one hand, cattle have been seen as one of the big causes of deforestation; on the other hand, when talking to the farmers, they had a strong relationship and love for cattle raising. Even though it is not cost-effective, they keep doing it because they are deeply connected to that activity. That leads me to think about our relationship with nature, including mine. What values do I have, and from where do they come? Why do we (I) see nature separated from people? In this regard, I was convinced that the leverage points theory (Abson et al. 2017) is confirmed and that it is at this in-depth value that we have to pay more attention to achieve sustainability.

Reflecting on the strategies for working with different values to foster effective dialogue, I learned not to take an emotional positionality immediately, to take some time to accept the discomfort or analyze incongruences, and to be aware of what does not check with my vision and values. I wonder if I can always listen with an open mind and heart.

I come back to feel proud of myself and my crossed boundaries. Proud to be here at the end of this PhD. Certainly, it has been the biggest challenge I have faced in all my life, but it has fulfilled me with courage and empowerment. Has unblocked my creativity and has given me new lenses. Has allowed me to connect with wonderful and amazing people. I am so grateful. Grateful for flourishing together without knowing where we are going in this transformative process because "a process is not a process when you already know how it is going to be like" (Leneke Pfeifer). On the other hand, maybe we are just idealistic people allowing themselves to dream together.

"Autorretrato" Patricia Santillán Carvantes. June 2023

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APPENDICES

APPENDIX 1. DECLARATION OF AUTHORSHIP

PhD candidate: Patricia Santillán Carvantes

Title: Linking biodiversity, nature's contributions to people, and good quality of life: insights from tropical dry secondary forests in Mexico

Declaration of authorship

According to §16 of the guideline of cumulative dissertations, the following section details my own individual contribution in preparing the three research articles. This entails specifying the individual scientific contributions of all co-authors, including me (author´s contributions), and the relative importance of my own contribution in relation to the contributions of other co-authors (declaration of authorship) together with a weighting factor.

Overview of articles included in the doctoral thesis

(in accordance with the Guideline for cumulative dissertations enacted at the Faculty of Sustainability in January 2012)

Authors' contributions to the articles and articles' publication status.

Chapter No.	Journal impact factor* and publication status	Specific contributions	Author status and weighting factor**	Presentation at conference
II	Ecology & Society (JIF= 4.65); under review	**Patricia Santillán-Carvantes**: Conceptualization, Formal analysis, Investigation, Writing – original draft, Visualisation. **Berta Martín-López:** Conceptualization, Writing – review & editing, funding acquisition, Supervision. **Manuel Pacheco Romero:** Writing – review & editing. **Maraja Riechers:** Writing – review & editing. **Patricia Balvanera**: Conceptualization, Writing – original draft, funding acquisition, Supervision.	Co-author with predominant contribution (1.0)	**10th World Conference Ecosystems Services Partnership.** Hanover, Germany. October 2019. *Poster presentation* **Ecosystems Services Partnership -LAC-2020** Conference. Mexico City, online. November 2020. *Oral presentation*
III	Landscape Ecology(JIF= 5.3); accepted	**Patricia Santillán-Carvantes**: Conceptualization, Formal analysis, Investigation, Writing – original draft, Visualisation. **Patricia Balvanera**: Conceptualization, Writing – original draft, funding acquisition, Supervision. **Simon Thomsen:** Spatial analysis, maps creation, Writing – review & editing. **Francisco Morales Padilla:** Data ownership (collection), Writing – review & editing. **Nathalia Pérez-Cárdenas:** Data ownership (collection), Writing – review & editing. **Daniel Cohen:** Data ownership (collection), Writing – review & editing. **Rubén Ramírez:** Data ownership (collection), Writing – review & editing. **Mayra Gavito:** Data ownership (collection), Writing – review & editing. **Berta Martín-López:** Conceptualization, Writing – review & editing, funding acquisition, Supervision.	Co-author with predominant contribution (1.0)	**VIII meeting of the Mexican Ecological Society**, Oaxaca, Mexico. May 2022. *Oral presentation*

IV	Sustainability Science (JIF= 7.4); ready to send	**Patricia Santillán-Carvantes**: Conceptualization, Formal analysis, Investigation, Writing – original draft, Visualisation. **Alejandra Tauro:** Data ownership (collection), Writing – review & editing. **Berta Martín-López:** Conceptualization, Writing – review & editing, funding acquisition, Supervision. **Juan Miguel Requena Mullor**: Writing – review & editing. **Antonio J. Castro**: Writing – review & editing. **Cristina Quintas-Soriano**: Writing – review & editing. **Patricia Balvanera**: Conceptualization, Writing – original draft, funding acquisition, Supervision.	Co-author with predominant contribution (1.0)	**4th Europe Ecosystems Services Partnership conference.** Heraklion, Greece. Online. October 2022. *Oral presentation*

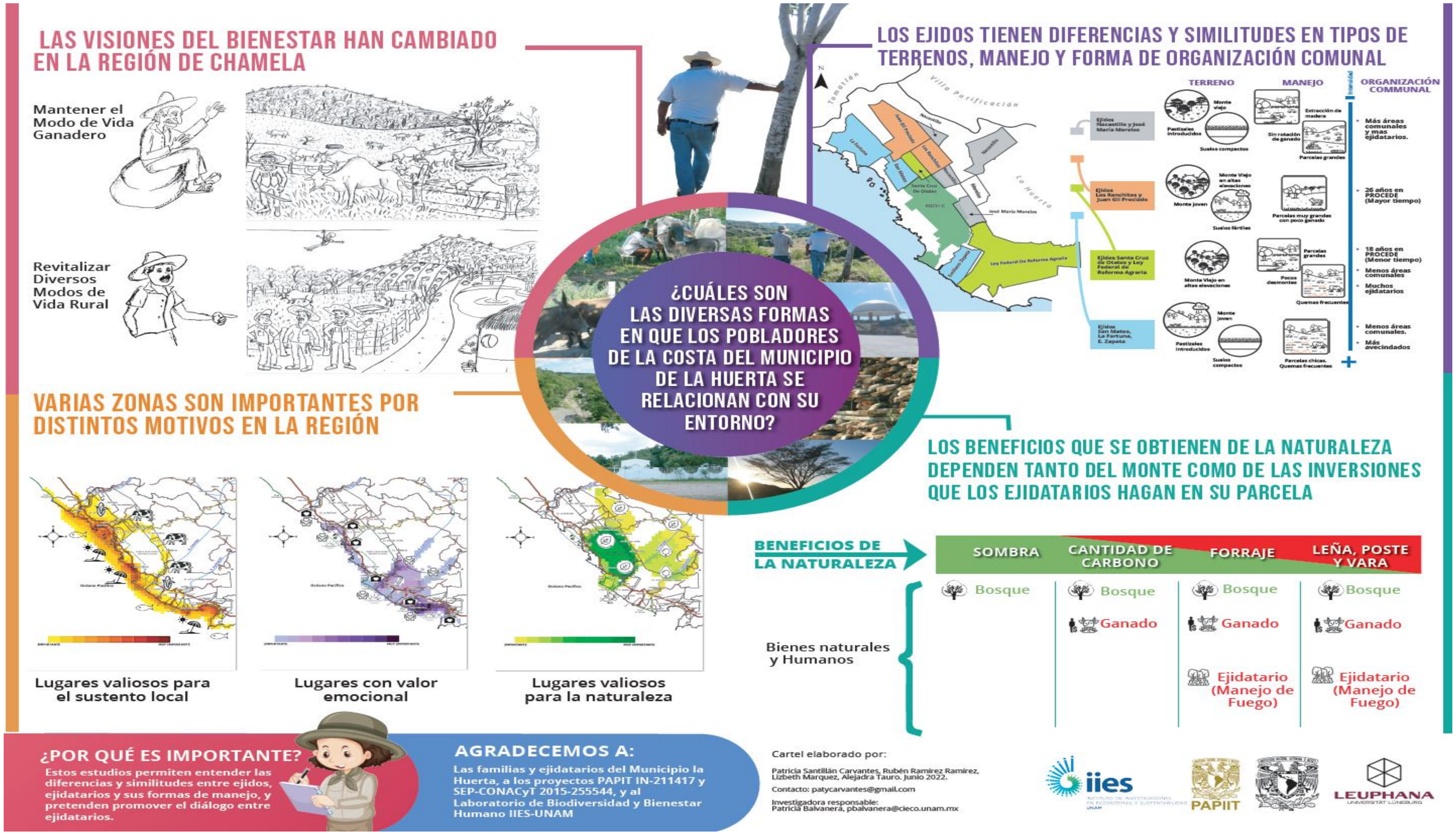
Explanation

* *2021 Journal Impact Factor* (JIF) based on data indexed in the Web of Science Core Collection; source: https://jcr.clarivate.com/jcr/browse-journals

**Author status and weighting factor* according to §12b and §14 of the guideline: Author status	Weighting factor
Single author [Allein-Autorenschaft] = Own contribution amounts to 100%.	1.0
Co-author with predominant contribution [Überwiegender Anteil] = Own contribution is greater than the individual share of all other co-authors and is at least 35%.	1.0
Co-author with equal contribution [Gleicher Anteil] = (1) own contribution is as high as the share of other co-authors, (2) no other co-author has a contribution higher than the own contribution, and (3) the own contribution is at least 25%.	1.0
Co-author with important contribution [Wichtiger Anteil] = own contribution is at least 25%, but is insufficient to qualify as single authorship, predominant or equal contribution.	0.5
Co-author with small contribution [Geringer Anteil] = own contribution is less than 20%.	0

I certify that all of the information given in this appendix is true, both individually and as a whole.

APPENDIX 2. POSTER DELIVERED IN JUNE 2022 TO THE *EJIDOS* THAT SURROUND THE CHAMELA-CUIXMALA BIOSPHERE RESERVE IN THE OUTREACH TOUR.



APPENDIX 3. PICTURES OF THE OUTREACH TOUR IN JUNE 2022

A) Presentation in the *Ejidal* Assembly in the *ejido* “Los Ranchitos”. B) Presentation of the results to an *ejidatario* (i.e., smallholder) in the *ejido* “Zapata.” C) Presentation of the results to an *ejidatario* in the community of Chamela. D) Presentation of the results to the people of the *ejido* “Nacastillo.”

Reflexiones entorno a la investigación en la Región de Chamela, en la costa del municipio La Huerta, Jalisco.

Se presentan a continuación las reflexiones producidas durante la reunión del 17 de junio de 2022 en el IIES (Morelia) sobre cómo podemos generar información más relevante para las personas de la región de Chamela y cómo podemos entregar mejor los resultados. Se agregan también otras ideas e iniciativas que fueron comunidacadas por investigadorxs que no pudieron estar presentes pero que están interesadxs en la discusión.

Contenido:

1. Participantes del taller y autopercepciones sobre su investigación en Chamela
2. Ideas vertidas, formas de generar información más relevante para las personas de la zona, obstáculos y acciones que lo facilitarían
3. Ideas vertidas, formas de entregar mejor los resultados y obstáculos identificados
4. Acuerdos
5. Sentires generales
6. Ideas e iniciativas compartidas extramuros
7. Nota final

1. Participantes del taller

Presencial	En línea
1. Patricia Santillán Carvantes	10. Rosa Sánchez
2. Rubén Ramírez	11. Sofía Monroy
3. Patricia Balvanera	12. Mariana Lagunas
4. Francisco Mora	13. Esther Aguilar Román
5. Harumi Takano Rojas	14. Liz Márquez
6. Landy Orozco	15. Horacio Paz
7. Gerardo Dávila	
8. Jessica Tovar	
9. Adriana Fournier	

Al inicio de la reunión, se invitó a presentarse con lo que han hecho en Chamela, lo que sintieron que fue de utilidad para las personas y lo que les hubierse gustado hacer.

Quienes participaron han trabajado en una diversidad de temas principalmente ligados al monitoreo, recuperación, productividad y manejo del bosque, vulnerabilidad y tipología socioambiental, percepciones y bienestar de las personas locales, y recarga de acuíferos.

Hay una preocupación generalizada sobre la incidencia y la trascendencia de la investigación, sobretodo en proyectos cortos como maestría o licenciatura. Se mencionaron como retos para ello, la cercanía con el lugar y el tiempo que toma construir relaciones de confianza para poder establecer trabajos transdisciplinarios.

La contribución más relevante de varios de los proyectos, ha sido el abrir espacios de diálogo que les permitan conocerse entre personas de distintos lugares y detonar reflexiones colectivas.

Otra convergencia fue que a la gente le interesa saber, conocer e integrarse en lo que estamos haciendo desde la academia, y que el compartir resultados e interactuar con las personas ha cambiado de alguna manera su percepción sobre el bosque y la naturaleza.

Dentro de lo que les hubiese gustado hacer, hay varias ideas en el tintero, por ejemplo:

- Hacer ciencia transdisciplinaria donde los ejidatarios sean parte del codiseño de la investigación
- Ciclo de cine en las comunidades con un documental sobre la importancia de los bosques en la recarga de los mantos acuíferos
- Dejar una estación meteorológica en la preparatoria de Miguel Hidalgo y usarlo como medio para trabajar más en conjunto con jóvenes
- Hacer un intercambio de experiencias entre ejidos (ej. la experiencia de la coperativa de mujeres que maneja recursos naturales en Cuzalapa, Sierra de Manantlán)
- Redireccionar la investigación hacia puntos clave en la zona: el agua y el turismo (privatización de las playas y el acceso)
- Enfocarse en el desarrollo de capacidades (ej. organización, participación)
- Dejar de ver a la gente local como “los que están degradando el sistema”
- Ampliar el vínculo entre la ciencia y la sociedad

2. Ideas vertidas, <u>formas de generar información más relevante</u> para las personas de la zona, obstáculos y acciones que lo facilitarían

Ideas	Obstáculos	Acciones que lo facilitarían
Plantear dentro de los objetivos específicos de los proyectos, la generación de información relevante y devolución de resultados	La devolución de resultados queda al último en la forma de plantear los proyectos, en el proceder de la ciencia y en el financiamiento	Cambiar nuestra manera de pensar en relación a lo científico y pensar que uno puede ser un agente de cambio e involucrarnos
Partir de necesidades locales y problemas concretos ya idenficados	Cambio de intereses en la gente local	Revisar información técnica, no sólo académica
Que las preguntas sobre intereses y necesidades permeen a las asambleas ejidales, no sólo a individuos.	Nivel de organización y acuerdos entre las comunidades y dentro de la academia	Realizar talleres de desarrollo de capacidades (ej. organización y comunicación) tanto dentro de la academia como en las comunidades.
	Falta de un lenguaje común Visión común entre academia y comunidades	Hacer la información más digerida para que haya más capacidad de difusión y comunicación
Identificar los mejores canales de comunicación por zona para que llegue de manera oportuna	Generación de fuentes de financiamiento con enfoque integral	Labor de convencimiento con instituciones para crear impacto social y cambiar indicadores del éxito científico (más allá de publicaciones científicas)
Identificar temas transversales aplicables a distintos laboratorios	Desarticulación de quienes investigan en Chamela	Organización de reuniones entre estudiantes e investigadorxs que están trabajando ahí
Reuniones de diálogo de “Chameleros” al menos una	Quién lo va a organizar. Responsabilidad de	

vez al semestre. Intercambio de experiencias	organización	
Conectar necesidades locales entre las comunidades para tener necesidades regionales (ej. problemática del agua)	Las problemáticas tienen diferentes escalas y hay que encontrar la manera de poder coincidir.	Mantener los vínculos y la comunicación con actores clave.
Co-diseño debe ser flexible para incorporar las necesidades a cualquier escala inclusive nacional	Es difícil dimensionar las problemáticas entre los actores.	Resolución de los conflictos es complicado cuando se es actor secundario, podríamos ser conectores.
Abrir línea de investigación-acción participativa/ Transdisciplianria	Generación de fuentes de financiamiento con enfoque integral	Que la Estación de Biología sea el punto de reunión para desarrollar los proyectos integrales

3. Ideas vertidas, <u>formas de entregar mejor los resultados</u> y obstáculos identificados

Ideas	Obstáculos
Hacer lineamientos éticos para la investigación en Chamela que sean parte del reglamento de la Estación Biológica	Responsabilidad de organización. Aplicación.
Que todos los proyectos tengan un componente explícito de comunicación de resultados	Financiamiento en los proyectos
Mecanismo real de seguimiento a largo plazo con presencia de un equipo constante en la Región. Contar con un "link" local, una persona que sea de la comunidad o muy relacionada con las comunidades que la gente lo asocie con la UNAM.	Financiamiento. ¿Qué laboratorio? ¿Cómo?
Coordinación entre laboratorios para entregar resultados en conjunto al menos una vez al año para tener una presencia constante.	Financiamiento. Tiempo. Interés. Coordinación
Retomar un espacio tipo "puertas abiertas" en la Estación de Biología	Interés de la Estación de Biología
Ir a los ejidos no sólo invitar a la Estación.	Financiamiento. Tiempo
Abrir espacios de diálogo con las personas, no sólo entregar folletos Preguntar a la gente en qué formato prefiere la entrega de resultados	Medios de comunicación y coordinación con personas locales. Datos de personas. Lineamientos éticos de privacidad y uso de datos
Entregar documentos con formato accesible (i.e. manta, cartel, material participativo). Usar formatos audiovisuales para whatsap y redes sociales. Videos cortos y podcasts (darle agencia a las personas, darle voz a sus voces)	Financiamiento de proyectos interdisciplinarios

Grupo de trabajo unificado de investigadorxs y estudiantes en Chamela para salir juntxs, sistematizar la información Mantener conexiones interinstitucionales y compartir los resultados ahí también (ej. Brigadas de incendios, Catie/BioPasos-Escuelas de Campo, Jilcosur)	Interés. Agendas

4. Acuerdos y propuestas durante la reunión.

1) Francisco Mora (Pacho), se autopropuso como organizador de una reunión semestral para intercambiar ideas, experiencias y sentires entre todas las personas trabajando en Chamela.

2) Paty Santillán se comprometió a hacer una minuta de la reunión, enviarla para el VoBo de lxs asistentes al taller, y finalmente compartirla con investigadoras.es del iies, así como a la dirección de la Estación Biológica.

3) Se propuso hablar con Leonor Solís para hacer una publicación respecto a lo aquí platicado en la página del iies, así como en un blog en internet donde quede esta información disponible [Falta persona responsable de esto].

5. Sentires generales

Las inquietudes aquí expresadas son sentires compartidos por estudiantes y por lxs investigadorxs presentes en la reunión. Hay un sentir general de entusiasmo de estar reunidxs reflexionando sobre estos temas que se resumen en estas palabras:

6. Ideas e iniciativas compartidas extramuros

<u>Alicia Castillo:</u>

"[...] tenemos una tesis muy avanzada (tesis conjunta de dos chicos) de la LCA y que es una propuesta de construcción de una plataforma digital que ayude / promueva / facilite la comunicación entre la diversidad de actores sociales que viven y trabajan en la región de la costa sur de Jalisco (comenzando con la parte costera del municipio La Huerta)”

“Aprovecho, asimismo, para ampliar la noción de lo que entre las y los académicos que estamos trabajando en la zona cercana a la Estación de Biología, llaman “Chamela”. Es en efecto, el nombre de la estación y de la comunidad que se encuentra más cercana a esta. Pero no es una región como tal (lo aclaro porque mencionas el trabajo en ejidos y la necesidad de tener impacto en la zona más allá de la estación de biología)”

“Decir [también] que tenemos un libro en prensa llamado “Apropiación social del conocimiento socio ecológico en México”, en el cual ponemos sobre la mesa el tema de la vinculación ciencia-sociedad en relación con lo ambiental. El libro saldrá en versión digital e impresa y esperamos compartirlo alrededor de septiembre (lo presentaremos en el Congreso Nacional de Educación Ambiental en octubre en Guadalajara). Con gusto les haremos llegar este producto que busca aportar ideas a la necesaria reflexión sobre qué, cómo y para quién hacemos ciencia.”

“[...] quizás les pueden ser útiles estos dos artículos que aquí comparto. El de 2018, recopila algunas experiencias de lo que un grupo de académicos (sobre todo estudiantes) hemos llevado a cabo en la costa (tiene una figura al final que es una propuesta para impulsar las interacciones de la academia con las comunidades rurales). El segundo [de 2021] lo hicimos para revisar y detonar reflexiones sobre el papel de las dos estaciones de la UNAM a 50 años de su creación. En este viene lo que te comenté de las necesidades e intereses de las familias.

Castillo, A., Vega-Rivera, J. H., Pérez-Escobedo, M., Romo-Díaz, G., López-Carapia, G., & Ayala-Orozco, B. (2018). Linking social-ecological knowledge with rural communities in Mexico: lessons and challenges toward sustainability. Ecosphere, 9(10), e02470. https://doi.org/10.1002/ecs2.2470

Castillo, A., Velasco-Morón, A., Arroyo-Arroyo, Y., Aranda-Fragoso, A., Aguilar-Román, E., Pérez-Escobedo, M., … Vega-Rivera, J. H. (2021). Two tropical research stations in Mexico: 50 years of contributions and challenges. Environmental Challenges, 3, 100037. https://doi.org/10.1016/J.ENVC.2021.100037

7. Nota final

La organización de este taller no tuvo por objetivo desarrollar ningún plan de acción respecto a las ideas aquí vertidas. La iniciativa de esta reunión viene de reflexionar en conjunto sobre los “problemas” y frustraciones de la investigación en la Costa de Jalisco que varixs estudiantes e investigadorxs compartimos. Muchxs de nosotrxs ya vamos de salida en nuestros proyectos de investigación, pero para quienes se quedan o a penas van empezando esperamos que estas ideas puedan aportar a una cordinación y organización que pueda generar información más relevante para las personas locales, y que su comunicación sea más efectiva.

APPENDIX 5. DECLARATION OF ORIGINALITY

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I hereby declare that I have never taken any doctoral examination or applied for admission to such examination.

I further affirm that the dissertation with the title “Linking biodiversity, nature’s contributions to people, and good quality of life: insights from tropical dry secondary forests in Mexico” has not been submitted to any representative of any faculty and that I am submitting the dissertation only in this and in no other Doctoral procedure and that no other definitely fail has been achieved in any previous Doctoral procedure.

I further declare, that I composed the submitted Dissertation “Linking biodiversity, nature’s contributions to people, and good quality of life: insights from tropical dry secondary forests in Mexico” independently and without having recourse to prohibited means. I have not used any aids or texts other than those I indicated. All passages taken in verbatim or substance from other works have been identified.

München, July 16th 2023

Patricia Santillán Carvantes

CHAPTER II. MONITORING SOCIAL-ECOLOGICAL SYSTEMS DYNAMICS: AN ANALYTICAL FRAMEWORK

"*Social-ecological thoughts"* Patricia Santillán Carvantes. June 2023

AUTHORS: Patricia Santillán Carvantes, Berta Martín López, Manuel Pacheco Romero, Maraja Riechers, Patricia Balvanera

TITLE

Monitoring social-ecological systems dynamics: an analytical framework

ABSTRACT

Analyzing the complexity of social-ecological systems (SES) represents an empirical challenge that requires analytical frameworks that can be applied across decision-making scales. Although global conceptual SES frameworks have seldom been applied at local scales, local monitoring of SES has rarely informed the design of SES frameworks. In this paper, through an iteration of global deductive and local inductive approaches, we develop an analytical and cross-scale framework, operationalize it at local decision-making scales, and assess its representability based on indicators already available in the Chamela-Cuixmala Mexico. Derived from the dimensions of nature's contributions to people (NCP), our framework comprises five key components: (1) *ecological supply*, (2) *co-production of NCP*, (3) *management, (4) demand*, and (5) *benefits.* We operationalize the framework at three local-decision making scales – i.e., an individual plot, smallholder, and land tenure – by identifying how 245 indicators were formerly used in the literature of Chamela-Cuixmala SES. The representability of the framework shows that research has emphasized the components of NCP *co-production* (42% of indicators) and SES *management* (21%). By analyzing SES dynamics through this new framework, we can support the monitoring of NCP and potentially detect regime shifts or radical changes before they are happening. The framework is at the same time context-specific and operationable across global contexts and, therefore, it provides an opportunity to inform discussions on global sustainability from local contexts.

KEY WORDS

Essential Ecosystem Services Variables; Global/deductive-local/inductive approach; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services; local decision-making scales; operationalization

ACKNOWLEDGMENTS

We gratefully acknowledge Dr. Alicia Castillo for providing access to the documentary database of the Chamela-Cuixmala Biosphere Reserve. The first author acknowledges the PhD scholarship received from Consejo Nacional de Ciencia y Tecnología (CONACYT) and the Deutscher Akademischer Austauschdienst (DAAD). She also thanks Lidia García and Aline Pingarroni for insightful discussions, exchanges, and comments on this paper.

INTRODUCTION

Analyzing the complexity of social-ecological systems (SESs) represents an empirical challenge, requiring analytical integrative frameworks that can be applied across decision-making scales. In the past decades, SES research has provided multiple frameworks to unpack the complexity of human-nature interactions across different spatial and temporal scales -for a review of SES frameworks, see Binder et al. (2013) and Biggs et al. (2021)-. Frameworks provide sets of assumptions and concepts with the aim to highlight, in an abstract manner, how a specific reality, system, or phenomenon is understood (Binder et al. 2013, Meyfroidt et al. 2018). Usually, frameworks are accompanied by a graphical representation that illustrates each concept and the interactions between them. Therefore, a framework is both a tool to analyze reality and a tool to communicate about this reality (McGinnis 2011, Díaz et al. 2015b, Meyfroidt et al. 2018).

SES frameworks, specifically, aimed to guide research by identifying the concepts, variables, and processes that are relevant to explain the dynamics of SES, predicting changes, or delineating management strategies toward sustainability (Biggs et al. 2021). In doing so, SES frameworks provide reference lists of variables that can represent the most relevant SES components and the interactions between them (e.g., Ostrom, 2009; McGinnis and Ostrom, 2014; Frey, 2017; Pacheco-Romero et al., 2020). Despite these developments, analytical tools that allow the assessment and monitoring of SES dynamics are still lacking.

To understand and monitor SES dynamics, the majority of SES frameworks emphasize the benefits that nature provides to people and how individuals and societies manage and impact ecosystems (e.g. Folke et al. 2002, Liu et al. 2007a, 2007b, Ostrom 2009, Fischer et al. 2015). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), for example, has developed a framework to assess the dynamics of SES at global and regional scales (Díaz et al. 2015a). The framework includes the concept of "Nature´s contributions to people" (NCP), which considers the multiple ways by which people relate with, demand, and value nature and its contributions (Díaz et al. 2015a, 2018, Pascual et al. 2017). In addition, the NCP framework explicitly acknowledges that these contributions are not only derived from nature but also require inputs from humans, a process known as "co-production" of NCP (Díaz et al. 2015a, Palomo et al. 2016, Bruley et al. 2021). Yet, the operationalization of this framework into lower scales than regional and global remains challenging and unexplored.

One challenge is the identification of the minimum set of variables to be monitored. Recently, researchers identified Essential Ecosystem Services Variables (EESVs) for NCP (Balvanera et al. 2022). The EESVs framework encompasses six comprehensive classes to monitor the interdependencies between nature and societies across space and time (Balvanera et al. 2022): (1) ecological supply, i.e. the ecosystems' structure and functions that lead to the provision of

NCP; (2) anthropogenic contribution, i.e. capitals used by people to enhance the ecological supply and co-produce NCP; (3) demand, i.e. the human desire and need for NCP; (4) use, i.e. the active or passive appropriation of NCP by social actors; (5) instrumental values, i.e.

the importance of NCP to people as a means to an end (Díaz et al. 2015a); and (6) relational values, i.e. the importance ascribed to how ecosystems contribute to meaningful interactions between humans and nature and between humans in relation to nature (Chan et al. 2016). Yet, to date, these EESVs have not been operationalized to monitor SES dynamics.

Previous efforts to operationalize SES frameworks at local scales have led to the characterization and mapping of SESs (Martín-López et al. 2017, Dressel et al. 2018, Rocha et al. 2020, Vallejos et al. 2020, Pacheco-Romero et al. 2021, 2022). However, to date, less emphasis has been placed on SES dynamics due to the challenges related to data collection and integrative analysis of social and ecological components as well as their interactions (e.g. (Basurto et al. 2013, Cox 2014, Leslie et al. 2015, Delgado-Serrano and Ramos 2015). Therefore, analytical frameworks that are able to monitor SES dynamics and support management decisions across scales are still lacking (Balvanera et al. 2017, Martín-López et al. 2020). Yet, such monitoring is crucial in light of environmental crises in order to understand transformative change and possibly even avert regime shifts (Hicks et al. 2016). Hence, the operationalization of analytical frameworks able to mobilize social-ecological information into the management of SESs, especially in vulnerable areas of the Global South, is one of the most urgent needs in place-based social-ecological research (Guerrero et al. 2018, de Vos et al. 2019).

The main goal of this study is to develop an analytical and cross-scale framework to monitor social-ecological system dynamics, based on the components of nature's contributions to people (NCP) that are relevant to assess social-ecological dynamics. By drawing on two global frameworks (i.e. IPBES and EESVs), we first aim to build an analytical framework that can be applied at different decision-making scales. Second, we operationalize such a framework for a Long Term Social-Ecological Research (LTSER) from the Global South at three decision-making scales. Long Term Social-Ecological Research platforms are networks of sites around the world that pursues the coordinated social-ecological monitoring of diverse SESs (Maass et al. 2016) and offer excellent settings to operationalize global SES frameworks in local contexts. Hence, these networks represent an opportunity to foster place-based social-ecological research, especially in understudied regions of the Global South (Shibata and Bourgeron 2011, Maass et al. 2016). Finally, we assess how our cross-scale framework can be applied in the Chamela-Cuixmala region by examining how indicators for key NCP components have been used in the scientific literature.

METHODS

The development of the analytical and cross-scale framework resulted from an iterative process including deductive and inductive approaches. The global frameworks of IPBES and EESVs set the basis for the deductive exploration of the research site. The review of the literature available for the Chamela-Cuixmala region fed the inductive design of the framework.

Development of the framework

Our framework was built upon the global IPBES and ESSVs frameworks (Fig. 1). From the IPBES framework (Díaz et al. 2015a), we focused on the interactions across its six main elements: 1) nature, 2) NCP, 3) anthropogenic capitals and assets, 4) institutions and governance systems, and other indirect drivers of change, 5) direct drivers of change and, 6) good quality of life. From the EESV framework (Balvanera et al. 2022), we incorporated three classes: 1) ecological supply, 2) co-production, and 3) demand (encompassing use and values). These three classes were the main skeleton of the IPBES elements interactions. After our inductive assessment, we also included the benefits from NCP and SES management as new components (Fig. 1), leading to a final set of five components: (1) *ecological supply*, (2) *co-production of NCP*, (3) *management, (4) demand*, and (5) *benefits from NCP*. After identifying these main components that are required to assess and monitor SES dynamics, we integrated them back into the IPBES framework. Additionally, for each component, we defined a set of subcomponents that guide the monitoring of SES dynamics.

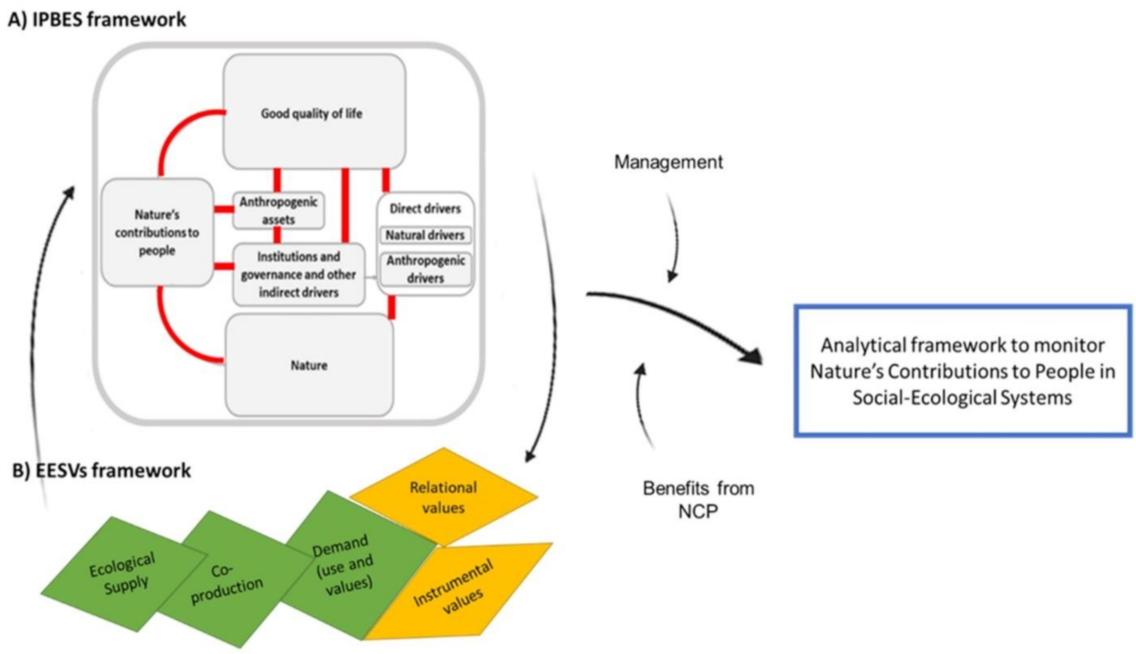

Figure 1. Analytical framework creation. A) Framework from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, Díaz et al. 2018). Arrows in red indicate the focus on the interactions of the proposed framework; B) The framework for the Essential Ecosystem Services Variables (EESVs, Balvanera et al. 2022), indicating those components used to guide the interactions among the elements of the IPBES framework. The components management and benefits from NCP were added to the proposed analytical framework after a literature review iteration.

Case Study

The Long Term Social-Ecological Research site Chamela-Cuixmala region is a biodiversity hotspot located in the state of Jalisco, Mexico. Ecologically, the region is mainly composed of a mosaic of tropical dry forests and grassland patches, but also of other ecosystems such as mangroves and wetlands. The outstanding biodiversity and the need to preserve it from land transformation led to the declaration of the central part of this region as the Chamela-Cuixmala Biosphere Reserve in 1993 (see Figure 2).

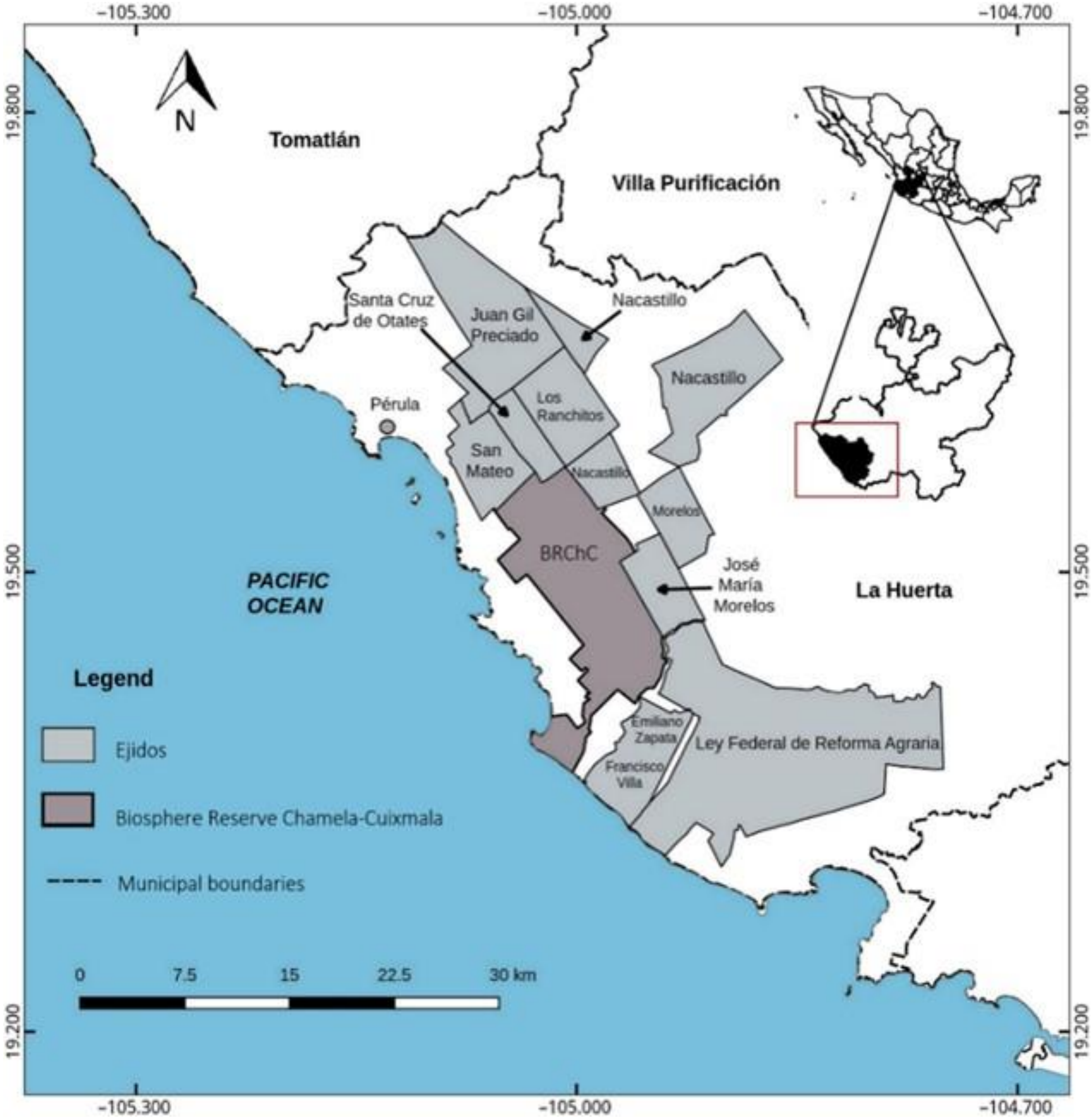

Figure 2. Location of the Chamela-Cuixmala region, comprised of the Chamela-Cuixmala Biosphere Reserve (BRChC) and the surrounding e*jidos*, in the state of Jalisco, Mexico. (Modified from Castillo et al. 2018).

The ownership regime is crucial for land management strategies in the Chamela-Cuixmala region (Monroy-Sais et al. 2018). Surrounding the Biosphere Reserve, there are 11 *ejidos*, i.e., land tenure units of tracts of land held in common by the inhabitants of a Mexican village and farmed cooperatively or individually. The *ejido* was conceived as a hereditary but unalienable semi-collective form of land tenure; these properties technically belonged to the federal government but were given to peasants between 1950-1975 as a result of the Agrarian Land Reform aimed to colonize the coasts of the country (Castillo et al. 2005, Lazos-Chavero et al. 2016). Each *ejido* member, called *ejidatario* (smallholder, peasant), had rights on the communal land allotted for the use of all registered families within the *ejido* through the *ejidal plot* (i.e. a portion of land where individual or communal decisions are made). In the Chamela-Cuixmala region, most of the tropical dry forests outside the Biosphere Reserve (ca. 70-80 %) are under the *ejido* tenure form (Sánchez-Azofeifa et al. 2009, Tauro et al. 2018).

The Chamela-Cuixmala Biosphere Reserve has belonged to the International Long-Term Ecological Research Network as a Long-Term Social-Ecological Research site since 1971. This nomination has fostered the study of the region from a transdisciplinary social-ecological perspective, particularly throughout the ecosystem service framework (e.g., Balvanera et al. 2011, Castillo et al. 2018, Cortés-Calderón et al. 2021). Such research has promoted that this region became one of the most studied tropical dry forest sites in the Neotropics (Noguera et al. 2002, Castillo et al. 2018), being an excellent case study for the operationalization of our framework.

Framework operationalization

To facilitate the operationalization of the proposed framework, we first identified three relevant local decision-making scales – i.e., individual plots, smallholders, and land tenures. Second, focusing on NCP as the key articulating element of the IPBES framework, we selected the most relevant NCP for the Chamela-Cuixmala region based on a universally applicable set of 18 categories that can be identified in a sharp, organized, and self-consistent system (i.e. the generalizing IPBES perspective, Díaz et al. 2018). Third, based on the Chamela-Cuixmala SES literature, we identified NCP based on local knowledge systems that might not be universally applicable (i.e. the context-specific IPBES perspective, Díaz et al. 2018), and related them to the generalizing categories. The final set of general NCP considered for operationalizing the proposed framework comprised eight NCP: (1) habitat creation and maintenance, (2) regulation of climate, (3) regulation of freshwater quantity location and timing, (4) formation protection and decontamination of soils and sediments, (5) food and feed, (6) materials, companionship, and labor, (7) learning and inspiration, and (8) supporting identities. Finally, we identified exemplary indicators available in the Chamela-Cuixmala region to monitor these NCP across the different local decision-making scales, components, and subcomponents of our analytical framework.

Assessing the representability of the cross-scale analytical framework

To assess the extent to which social-ecological dynamics can be monitored across local decision-making scales, we identified readily available indicators for the Chamela-Cuixmala region. We collected all available social-ecological indicators by performing a systematic review of the scientific and gray literature studying social-ecological dynamics in the Chamela-Cuixmala region for the period 2008-2019. We considered two literature repositories to conduct the literature review. First, for the literature published between 2008 and 2016, we used the documentary database of the Chamela-Cuixmala Biosphere Reserve (2008-2016). Second, for the literature published in the period 2016-2019, we used the repository of the Universidad Nacional Autónoma de México (tesiunam.dgb.unam.mx), Google Scholar, Web of Science, Redalyc, the repository of the Universidad Michoacana (bibliotecavirtual.dgb.umich.mx/) and the repository of the Universidad de Guadalajara (https://riudg.udg.mx/). The search string to conduct the literature review included key terms in Spanish and English referring to the region (e.g., "Jalisco AND Chamela", "Chamela"), to its main ecosystem ("Tropical Dry Forest"), to NCP (e.g. "ecosystem service*") and to "management". For the complete search string, view Appendix 1.

This search yielded 472 theses (251 B.Sc., 154 M.Sc., 67 Ph.D.) and 673 scientific articles. We screened these documents to keep only those that empirically explored social-ecological dynamics in the Biosphere Reserve surroundings, where people and nature interact directly. We obtained a final set of 15 scientific papers and 15 theses (Appendix 2).

From each document, we extracted all social and ecological indicators used to monitor the five components identified in the analytical framework (ecological supply, co-production of NCP, management, demand, and benefits from NCP), leading to a final set of 881 indicators. Then, we selected those indicators that were frequently used across space (i.e., used in at least five tenure units) and time (i.e., used for at least five years). For the case of social and management indicators, the time aspect was excluded due to the lack of long-term empirical social research in the region. After the selection by space and time, we merged redundant indicators when they measured the same component or dynamics. We obtained a final set of 245 indicators (Appendix 3). Finally, we classified each indicator into the different components and subcomponents of our framework and identified the decision-making scale in which they were used.

RESULTS

Analytical framework to study social-ecological dynamics

Our iterative deductive/global-inductive/local explorations informed the identification of five social-ecological components, namely *ecological supply*, *co-production*, *management*, *demand* (encompassing *use and values*), and *benefits from NCP*, that articulate the interactions across key elements of the IPBES framework (Fig.3). These five components have been identified as crosscutting variables to analyze SES dynamics. For each component, we identified relevant subcomponents that refer to different social-ecological attributes and processes (Table 1; for a detailed explanation of the subcomponents, see Appendix 4). To enable the identification of variables that can monitor the different subcomponents, we consider a set of guiding questions (Table 1).

Figure 3. Analytical framework incorporating five social-ecological components across the interactions among the elements of IPBES framework that drive the dynamics of SES: *ecological supply*, *co-production*, *management*, *demand* (encompassing *use and values*), and, *benefits from Nature's Contributions to People*. The five components, in colors, represent the flows of material, decisions, and values around NCP within a SES. Grey boxes represent IPBES's original elements. Dotted arrows represent IPBES's original linkages. Black arrows represent new interactions proposed in this framework.

Although these components represent different conceptual notions, they can overlap and interact in complex ways (Fig. 3; interactions between components are indicated by arrows). For example, the sense of achievement of a good quality of life directly depends on how the NCP *demands* are satisfied, how NCP benefits are appropriated (*use),* and what is considered important for fulfilling a life that it is worthy to live (*values*). For example, in the Chamela-Cuixmala region, people's sense of a good quality of life depends on the common identity built around cattle and, therewith, on the relational value of cultural identity (Tauro et al. 2018).

At the center of the framework, we placed the component of *NCP co-production* since it often modulates the supply of NCP, how people benefit from and demand NCP as well as how people manage NCP (Fig. 3). For instance, *the ecological supply* of fodder by the *Acacia sp*. "Huizache" in the Chamela-Cuixmala region is only possible through the knowledge of which species to keep and how to grow them (i.e., human capital from co-production) and the machinery used to cut down trees (manufactured capital) (Ramírez-Ramírez et al. *in review*). The intensity by which a smallholder uses the machinery to benefit from fodder defines the management strategy and, therefore, *co-production* also affects *ecological supply* through *management*. *Co-production of NCP* also affects how people *benefit from NCP*. For example, those people who received remittances (financial capital) are more likely to construct facilities to store and save water, leading to water security (i.e. *benefits from NCP*) (Cohen-Salgado 2014). Moreover, *co-production* might be also affected by the *demand: use priorities and values.* For example, the value systems of smallholders in the Chamela-Cuixmala region determine how much financial capital is invested in bovine production: when farmer's value systems are dominated by instrumental values, they invest a higher amount of money (financial capital) to gain greater financial benefits (Sánchez Martínez 2016). The way co-production is modulated by the *demand* and by governance leads to different *management* (Fig. 3). For example, in the Chamela-Cuixmala region, management decisions such as the number of cattle introduced in a pasture, are modulated, among other reasons, by the subsidies promoted by, for example, "Livestock Productivity Stimulus Program (Programa de Estímulos a la Productividad Ganadera, PROGAN)" (Schroeder and Castillo 2013, Tauro et al. 2018).

Table 1. Framework's components description, its subcomponents and guiding questions for monitoring

Component	Description	Subcomponents	Guiding question for monitoring	References
Ecological supply	Elements from nature that underline the potential capacity of ecosystems to provide NCP	Structure Species Function	What nature's elements contribute to the delivery of specific NCP?	Balvanera et al. (2022) Pereira et al. (2013)
Co-production	Process in which humans invest to enhance ecological supply and to make use of NCP	Social capital Human capital Manufactured capital Financial capital	Which anthropogenic capitals take part in the process of generating and delivery of specific NCP?	Balvanera et al. (2022) Palomo et al. (2016) Isaac et al. (2022)
Management	Decisions that contribute to increase or decrease the supply of a desired NCP	Time Intensity Extension	What decisions in the land modify ecosystem conditions to increase the	Van Oudenhoven et al. (2012) Trilleras et al. (2015)

			supply of desired NCP?	Zermeño-Hernández et al. (2015) Pérez-Cárdenas et al. (2021)
Demand (use and values)	Human desire or need for an NCP and, therefore, it encompasses dimensions of use and value. While use refers to an active or passive appropriation of a NCP, values are the importance that societies or individuals give to specific NCP. We consider only values describing meaningful interactions between humans and nature.	Priorities of use Instrumental values Relational values	How values can shape the co-production of specific NCP in order to achieve good quality of life?	Balvanera et al. (2022) Chan et al. (2016) Pascual et al. (2017) Arias-Arévalo et al. (2017)
Benefits	Elements that contribute the most to having a good quality of life	Good social relationships Good health Livelihood security Energy security Food security Water security	Which are the key benefits from specific NCP that contribute the most to people's quality of life?	MA (2005) IPBES (2018 ECA report)

Operationalization of the analytical framework across local decision-making scales

Our proposed framework focuses on identifying opportunities for action at local decision-making scales through NCP monitoring. In total, we identified 14 context-specific NCP for the Chamela-Cuixmala region, which were related back to eight generalizing NCP categories (Table 2). For each NCP, we also identified a set of exemplary indicators that were widely used at different decision-making scales in the Chamela-Cuixmala region to monitor each component and subcomponent (Table 2). Three decision-making scales were considered to operationalize the framework: individual plots, smallholders, and land tenure units.

Individual plots refer to the parcels of land owned by the smallholders, being the finest spatial decision-making scale. Many ecological studies collect and analyze their data using individual plots as the unit of analysis (Felipe-Lucia et al. 2020, Pérez-Cárdenas et al. 2021). For example, in the Chamela-Cuixmala region, soil research has largely been conducted at this scale evidencing the effect of deforestation and burnings on soil fertility (García-Oliva et al. 1999, Ellingson et al. 2000).

Smallholders refer to the plot owners who have land tenure rights and take decisions on their land. Smallholders are often considered key stakeholders in many long-term social-ecological research sites since their management decisions have a direct impact on the land (Maass et al. 2016). For example, in the Chamela-Cuixmala region, smallholders' information needs have been identified to manage the land (Castillo et al. 2018).

Land tenure units refer to the minimum governance unit where either legal or communal informal decisions take place. Within a land tenure unit, different individual plots may be contained. This scale is particularly relevant when connecting institutions and ecosystems since this unit is often the one at which census data is the finest and publicly available (Vallejos et al. 2020). For example, in the Chamela-Cuixmala region, the federal government launched the program PROCEDE (Program for Certification of *Ejido* Rights and Titling of Urban Plots) which allowed the privatization of an *ejido* (Schroeder and Castillo 2013). Privatization of *ejidos* fragmented smallholder communities, which led to weakening *ejido* institutions and local governance (Schroeder and Castillo 2013, Lazos-Chavero et al. 2016). However, depending on the *ejido* and its self-organization the impact of that reform has had a greater or lower impact on forest management and collective action management (Schroeder and Castillo 2013, Monroy-Sais et al. 2020).

Table 2. Exemplary operationalization of the analytical framework and decision-making scales in which the given indicator has been used to analyze and monitor NCP in the Chamela-Cuixmala SES. Complete references are provided in Appendix 2. IP= Individual plot, SH= Smallholder, LT= Land tenure

				Components and subcomponents of the analytical framework																				
				Ecological supply			Co-production				Benefits						Demand: use and values				Management			
NCP generalizing perspective	Context-specific NCP	Indicator	Units	Ecosystem structure	Ecosystem function	Species population	Human capital	Social capital	Finance capital	Manufactured capital	Good social relationships	Good health	Livelihood security	Energy security	Food security	Water security	Values	Instrumental values	Relational values	Priorities of use	Time	Intensity	Extension	Reference
NCP1. Habitat creation and maintenance	Pasture availability	Richness of herbaceous vegetation	rarefaction of observed herbaceous *spp*		IP																			22
NCP1. Habitat creation and maintenance	Types of ecosystems	Land use cover	% or ha	IP, LT																				21
NCP4. Regulation of climate	Economic valuation of climate regulation	Economic valuation carbon stock	USD ha^{-1}														SH	SH						12
NCP4. Regulation of climate	Shade for livestock	Carbon stock	T ha^{-1}		IP																			14
NCP6. Regulation of freshwater quantity, location and timing	Water availability	Access to water	Number of wells per cover type					IP, SH					IP, SH			IP, SH								13

NCP8. Formation, protection and decontamination of soils and sediments	Soil erosion prevention	Elevation	m	IP, LT											30
NCP12. Food and feed	Use of forest	Edible products harvested	kg extracted per cover type	SH		SH			SH	SH					13
NCP12. Food and feed	Use of exotic species	Fodder species	*spp*			SH		SH							13
NCP12. Food and feed	Pasture for livestock	Biomass fodder plants	t ha^{-1}	IP											25
NCP13. Materials, companionship and labor	Access to the land	Distance to the road	km				IP								7
NCP13. Materials, companionship and labor	Fodder production capacity	Planted pasture surface	ha			IP, SH, LT		IP, SH, LT						IP, SH, LT	5
NCP13. Materials, companionship and labor	Production capacity	Number of owned plots per *ejidatario*	count					SH	SH						13
NCP15. Learning and inspiration	Connection with the forest	Number of useful tree species identified per *ejidatario*	count	SH	SH	SH			SH				SH		28
NCP17. Supporting identities	Connection with the landscape	Sense of identity	Relative importance per cover type								SH	SH			13

Framework representability in our empirical case study

The assessment of the framework through analyzing the existing scientific literature of the Chamela-Cuixmala region shows the paramount importance of *co-production* since 42% of the indicators used referred to this component (Fig. 4). Twenty-one percent of indicators referred to *management* and 18% to *ecological supply* (Fig. 4). These three components, out of the five that make up this framework, covered 81% of indicators used in the region to monitor social-ecological dynamics (Fig. 4).

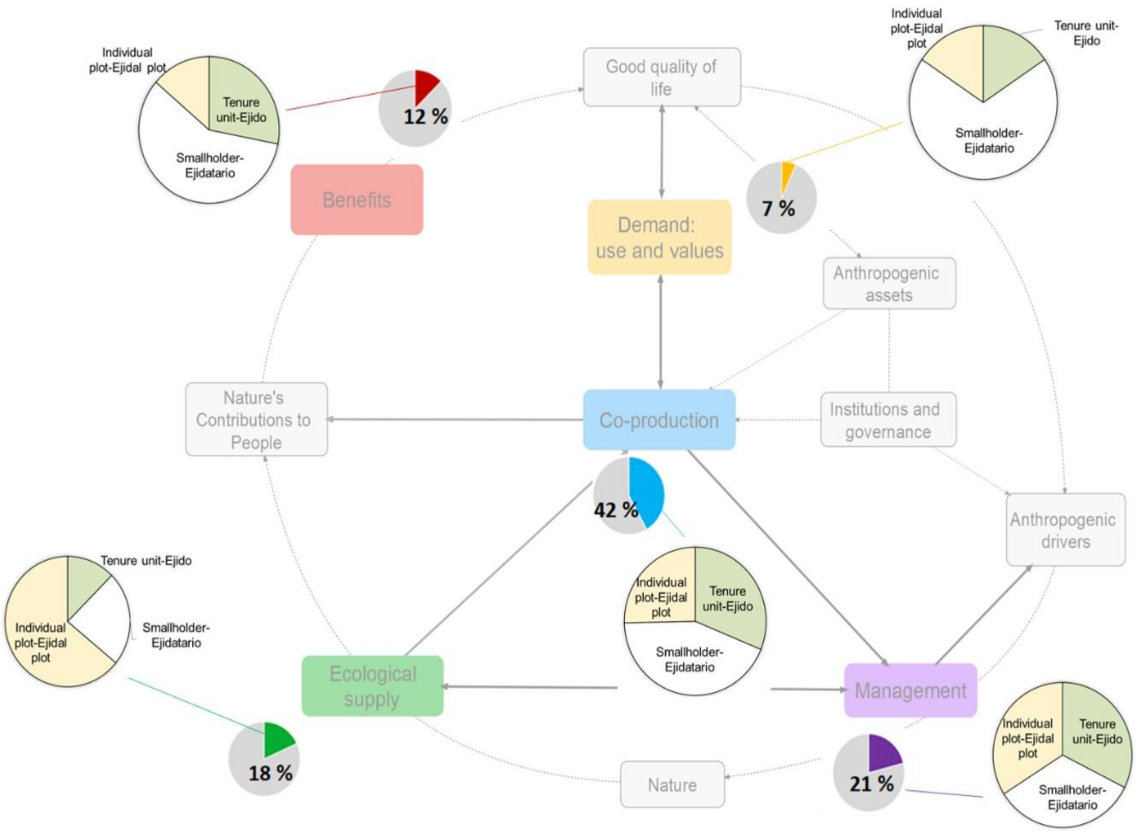

Figure 4. Percentage of indicators per social-ecological components. Bigger pie charts indicate their percentages per local scale: individual plots, smallholders, and land tenure units. Note that one indicator could be classified in more than one component or scale.

The operationalization of this framework for the Chamela-Cuixmala region allowed the identification of indicators that have been used to monitor the five components and their subcomponents across the three decision-making scales (Table 2). Overall, we found a connection between the indicators used to monitor each component and the scale at which the data is available (Fig. 4). While *ecological supply* was largely assessed by using indicators measured at the individual plot scale (64 % of indicators); *demand* and *benefits* from NCP were largely monitored at the *smallholder* scale (68 % and 58 %, respectively). For example, to monitor the regulating NCP of habitat creation and maintenance, many studies used the indicator ‘richness of herbaceous vegetation’ (i.e. *ecological supply*) that was measured at the *individual plot* scale. For monitoring the NCP of regulation of climate, some studies used the indicator “Economic valuation of carbon stock” (USD ha-1, i.e. *demand*) that was inquired at the smallholder scale. Similarly, for the NCP regulation of freshwater quantity, the indicator “access to water” was measured by the number of wells per cover type that each smallholder had (i.e. *benefits* from NCP).

The components of *co-production* and *management* have been assessed by using an even number of indicators at the three scales (Fig. 4). For instance, the indicator ‘pastureland surface’ that is used to monitor the material NCP of fodder was measured across scales. When ‘pastureland surface’ was measured at the *individual plot* scale, it indicated how people manage their plots (Trilleras et al. 2015). When it was measured at the *smallholder* scale, it monitored the smallholders’ decisions on how much of their land is devoted to cattle ranching (Pérez-Cárdenas et al. 2021). Finally, when it was measured at the scale of the *land tenure unit*, it represented how collective decisions are expressed in the communal land (Cohen-Salgado 2014, Monroy-Sais et al. 2020).

We also found that some subcomponents were monitored more frequently than others to assess a particular component (Fig. 5). *Ecological supply* was mainly assessed across scales by indicators referring to the ecological structure (40% of indicators within the *ecological supply* component), such as plant biomass, forest cover, land use or soil depth. Indicators representing ecological functions (38% of indicators within the *ecological supply* component), such as evapotranspiration, organic material, or net primary productivity, were only measured at the *individual plot* scale.

The *co-production* component was largely assessed across scales through the exploration of the human resources needed to manage their plots (e.g., skills, knowledge), i.e., human capital (57% of the total indicators within *co-production of NCP*). The component of *management* was mainly assessed with indicators representing intensity (40% of total indicators within management), such as burning frequency or cattle density, as well as representing time (38%), such as the number of years managing the plot. To monitor the *demand*, most studies used indicators collected at the *smallholder* scale referring to values in general (56% of total indicators within *demand*). Finally, most indicators used to measure *benefits from NCP* referred to smallholders’ livelihood security, such as income strategies (58% of total indicators within *benefits*), which was largely assessed across scales (Fig. 5).

Moreover, the assessment of the indicators used to monitor the different components in the Chamela-Cuixmala region revealed that while ecological studies used a small set of indicators to measure *ecological supply*, studies measuring *co-production* components led to a proliferation of indicators across scales, particularly for the subcomponent of human capital (Fig. 5).

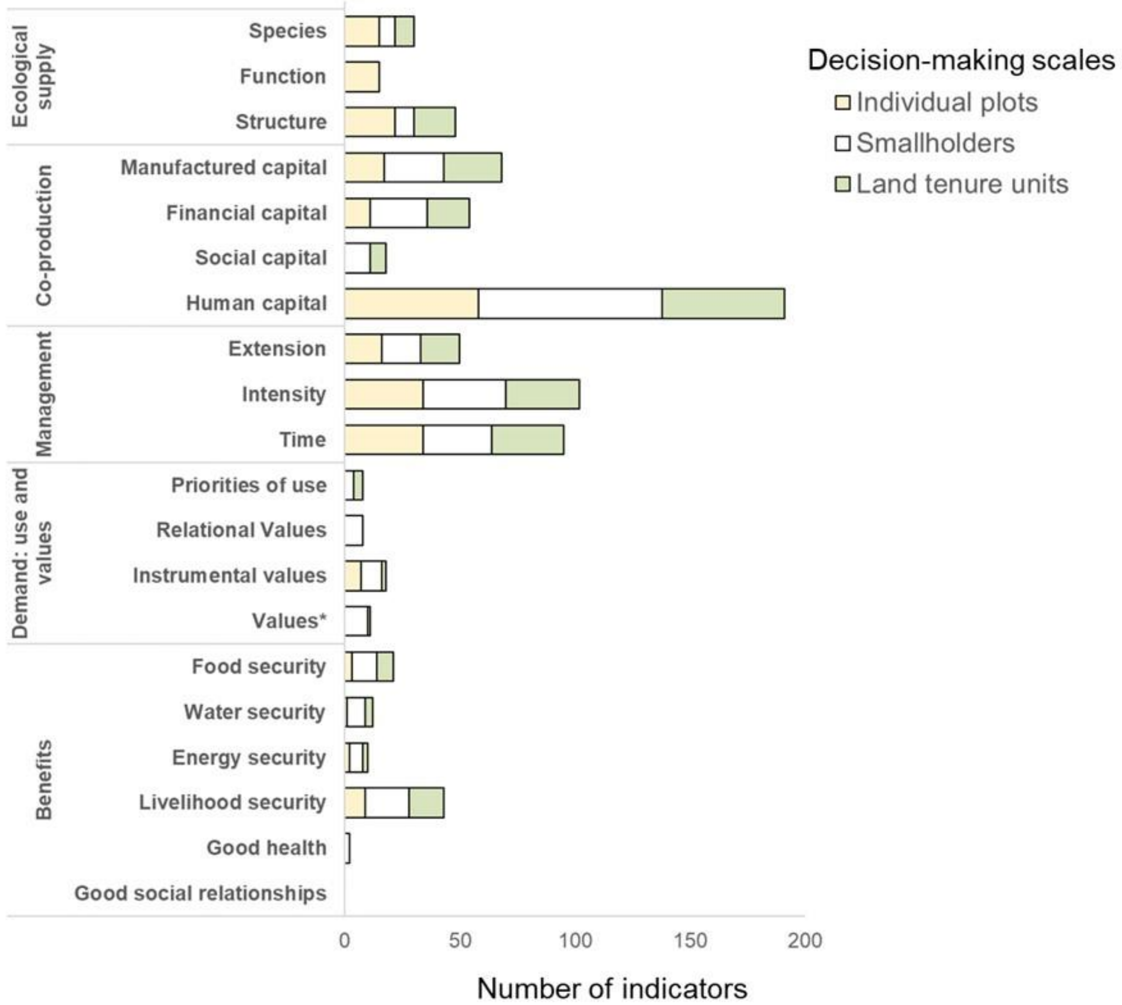

Figure 5. The number of indicators used to monitor the different components and subcomponents of the SES framework in the Chamela-Cuixmala region across decision-making scales. *We could not distinguish the meaning of some indicators used for NCP *values* and therefore unable to classify them into relational and instrumental values.

DISCUSSION

In this study, we have developed an analytical framework to understand SES dynamics through the monitoring of NCP, operationalized it across decision-making scales, and tested its representability in a case study of the Global South. In the following, we discuss the framework´s innovations, insights gained from its application in the Chamela-Cuixmala region, and its limitations.

A novel way to monitor social-ecological dynamics: integrating IPBES and EESV frameworks

The framework proposed in this study incorporates five components to analyze the dynamics of SES through the boundary object of NCP: *ecological supply*, *co-production, management, demand* (encompassing *use* and *values*), and, *benefits from NCP*. Among these components, we found that *management* and *co-production* are essential to modulate SES dynamics. This result aligns with the findings by (Torralba et al. 2017), who explain how management decisions determine the biophysical and sociocultural factors underpinning NCP co-production. Likewise, Bruley et al. (2021) found that the management of the ecosystem is an essential type of modulating NCP co-production. Therefore, we argue here that management and co-production are essential SES components that shape social-ecological dynamics.

Moreover, our analytical framework advances the IPBES and EESV frameworks in three different ways: 1) the integration of anthropogenic assets and governance as key elements of the *NCP co-production*, 2) the integration of the different values associated with the interaction between people and nature, and 3) the operationalization of the NCP concept across scales. First, the integration of anthropogenic assets and governance as key elements of NCP co-production to study SES dynamics can provide useful information to determine management strategies that sustain the flow of NCP (Palomo et al. 2016, Isaac et al. 2022). Second, the consideration of the *NCP demand* as the component that modulates not only co-production but also people's quality of life (Fig. 3, Tauro et al. 2018, Bruley et al. 2021). The consideration of *NCP demand* as a relevant component that mediates people's quality of life has been identified as one of the most important knowledge gaps to achieve sustainability (Mastrángelo et al. 2019). Finally, the operationalization of the NCP concept through interweaving both the context-specific and generalizing NCP perspectives enables the opportunity to represent social-ecological dynamics for different scales (Hill et al. 2021). Combined with these novel elements, our framework allows for a comprehensive assessment and monitoring of SES dynamics across time- and governmental scales.

Framework operationalization: insights from a Global South case study

The operationalization of our framework in the long-term social-ecological research site of Chamela-Cuixmala showed (a) the central role of *NCP co-production*, (b) differences in the availability and standardization of the indicators, and (c) varying levels of operationalization depending on the decision-making scale.

First, the operationalization of the framework demonstrates the central role that *NCP co-production* plays in the analysis of social-ecological dynamics across scales (see also (Reyers et al. 2013, Spangenberg et al. 2014). In particular, we found that human capital was a major subcomponent when monitoring the co-production of NCP, particularly food and feed, in the Chamela-Cuixmala region (Table 2). This result is aligned with previous studies that show the importance of anthropogenic assets for the supply of material NCP (Isaac et al. 2022, Ramírez-Ramírez et al. *in review*).

Second, we found substantial differences in the general level of availability and standardization of the indicators for the components and subcomponents of the framework. For instance, the indicators of the component ecological supply were mostly related to plant biomass, species richness, forest cover, soil properties, plant density, and species abundance (Appendix 2). All of these indicators are commonly standardized and available in ecological databases and their quantification is rather simple at the individual plot scale (Biggs et al. 2021 p. 95). Similarly, the high standardization level and quantitative nature of management indicators were observed across the three decision-making scales and for all the subcomponents (time, intensity, and extension) (Trilleras et al. 2015, Sánchez-Romero et al. 2021, Pérez-Cárdenas et al. 2021). By contrast, although co-production indicators were widely used (42% of the total indicators), the context-specificity of the capitals involved may explain the wide diversity and low standardization of indicators used in the Chamela-Cuixmala region. For example, Grosinger et al. (2021) found that for the supply of fodder in a French Alpine agricultural system there were several anthropogenic capitals involved, including technological equipment, such as irrigation and machinery, financial capital to purchase land or knowledge and skills to decide when to harvest. Finally, we found that, in the Chamela-Cuixmala region, there is a knowledge gap regarding the use of indicators to monitor *demand* (7%) and *benefits from NCP* (12%). This finding mirrors the results of former research that showed the lack of standardization of indicators to monitor NCP use and values (Arias-Arévalo et al. 2017, Mastrángelo et al. 2019, Schröter et al. 2020).

Third, we found that the potential of monitoring the five components varied according to the decision-making scales. For example, our results showed that *NCP demand* is more suitable to be monitored at the smallholder scale, which aligns with former research on values (e.g. Arias-Arévalo et al. 2017, Schmitt et al. 2022). Yet, the effect of people's values on management results in changes at the land tenure scale (Pingarroni et al. 2022, Santillán-Carvantes et al. 2023). This example illustrates the mismatch between the scale suitable for monitoring indicators and the scale where management is reflected. Therefore, by including three local decision-making scales in a framework to monitor SES, we can show the distinctive, yet interrelated nuances of social-ecological dynamics.

Framework limitations and outlook for the future research agenda

Although the operationalization of the suggested framework revolved around the beneficial NCP, the NCP paradigm also considers the detrimental contributions from nature to people, such as disease transmission or predation that damages livestock (Díaz et al. 2018). We believe that future research can apply this framework to assess both beneficial and detrimental contributions, how they impact people's quality of life, potential conflicts between stakeholders or who are the winners and losers. The application of the framework can expand recent research that has assessed both the beneficial and detrimental contributions (e.g. Morales-Reyes et al. 2018, Pascual-Rico et al. 2021) to evaluate the effectiveness of management strategies to enhance the sustainable flow of beneficial NCP while reducing impairments from nature and potential conflicts between stakeholders.

Moreover, we found that *NCP co-production* and *management* are central to mediating social-ecological dynamics; we did not examine what role power relations pose when mediating co-production and management. Power relations shape the *management* of NCP and their *co-production* by influencing how stakeholders can access and benefit from NCP (Chaudhary et al. 2018) or access and use the capitals underpinning *NCP co-production* (Vallet et al. 2019), as well as by determining who can participate in the management of NCP (Felipe-Lucia et al. 2015, Berbés-Blázquez et al. 2016). Despite the relevance of power relations mediating social-ecological dynamics, they remain an essential knowledge gap, and recent voices have called for the need to study how power operates shaping the NCP supply, demand, and governance to lever sustainability and social justice (e.g. Mastrángelo et al. 2019, Vallet et al. 2019, Martín-López et al. 2019). Future research applying the proposed framework can contribute to analyzing who exerts power over whom when managing the capitals behind *NCP co-production* and at what scale and how power is exerted in practice (Barnaud et al. 2018, Vallet et al. 2019, Martín-López et al. 2019) to determine how power can be effectively exercised to foster sustainable and just *management* of NCP.

CONCLUSION

The proposed framework allows its use from empirical research to gain an understanding of social-ecological dynamics and to provide insights that contribute to the sustainable and just *management of NCP*. Although it seeks knowledge generalization and indicator standardization, it is intendedly designed to be versatile and flexible to meet the particularities of diverse contexts. Different research questions that can be answered with this framework are related to 1) social-ecological characterization, 2) identification of relevant components and subcomponents determining social-ecological dynamics, and 3) identification of key indicators at different local decision-making scales that allow for the monitoring of SES. Therefore, this study provides an analytical way to operationalize global frameworks to monitor social-ecological dynamics across local decision-making scales. Moreover, the inductive identification of interdependencies between nature and people from an empirical Global South case study contributes to informing and further developing global sustainability frameworks.

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APPENDICES

Appendix 1. Search string to conduct the literature review

We used the following search string: "Jalisco AND Chamela", "Chamela", "Bosque Tropical", "Bosque Tropical Seco", "Bosque Tropical Seco AND Jalisco", "Bosque Tropical Seco AND Chamela", "Cuixmala", "Servicios ecosistémicos AND México AND Cuixmala", "Manejo AND Bosque Tropical Seco", "Manejo AND Bosque tropical seco AND Mexico", "Tropical Forest", "Tropical Dry Forest", "Tropical Dry Forest AND Jalisco", "Tropical Dry Forest AND Chamela", "Ecosystem Services AND Mexico AND Cuixmala", "Management AND Tropical Dry Forest", "Management AND Tropical Dry Forest AND Mexico".

Appendix 2. List of references used for indicators extraction

Number	Type of document	Reference
1	Thesis	Chirino Valle, I. (2008) *Almacenes y Fracciones de Fósforo en el Suelo de Tres Ecosistemas en la Región de Chamela, Jalisco.* Universidad Nacional Autónoma de México.
2	Thesis	Romero Duque, L. P. (2008) *Diversisdad y almacenes de carbono y nitrógeno en bosques tropicales caducifolios secundarios de la región de Chamela, Jalisco, con diferentes historias de uso*. Universidad Nacional Autónoma de México
3	Thesis	Saldaña Espejel, A. (2008) *Prioridades de restauración para la recuperación de servicios ecosistémicos asociados a los aspectos hidrológicos de la Cuenca del Río Cuitzmala, en el Pacífico Mexicano*. Universidad Nacional Autónoma de México.
4	Thesis	Solórzano Murillo, L. S. (2008) *Percepciones sobre servicios ecosistémicos relacionados con el agua en comunidades rurales de la Cuenca del rio Cuitzmala, Jalisco*. Universidad Nacional Autónoma de México.
5	Thesis	Trilleras Motha, J. M. (2008) *Análisis socio-ecológico del manejo, degradación y restauración del bosque tropical seco de la región de Chamela-Cuixmala, México.* Universidad Nacional Autónoma de México.
6	Thesis	Galicia Castillo, R. C. (2009) *Historia socio-ecológica y percepciones sociales sobre el bosque tropical seco en un ejido de la región de Chamela-Cuixmala, Jalisco*. Universidad Nacional

		Autónoma de México.
7	Thesis	Martínez Harms, M. J. (2010) *Cuantificación y mapeo de servicios ecosistémicos en una cuenca mexicana: implicaciones para su conservación y manejo*. Universidad Nacional Autónoma de México.
8	Thesis	Trilleras Motha, J. M. (2015) *Régimen de Manejo, servicios ecosistémicos y capacidad adaptativa en un sistema manejado de una región tropical seca*. Universidad Nacional Autónoma de México.
9	Thesis	Cardona Valadez, L. M. (2013) *Respuesta de las propiedades del suelo de parcelas ganaderas de Chamela, Jalisco, a tratamientos de sombra y adición de materia orgánica con fines de recuperación de algunas funciones ecosistémicas del suelo*. Universidad Nacional Autónoma de México.
10	Thesis	Cohen Salgado, D. (2014) *Estrategias de manejo del bosque tropical seco: un estudio de caso en Jalisco*. Universidad Nacional Autónoma de México.
11	Thesis	Ugartechea Salmerón, O. A. (2015) *Valor económico y disyuntivas ambientales en el manejo del bosque tropical seco en Chamela, Jaliscco*. Universidad Nacional Autónoma de México.
12	Thesis	Naime Sánchez Henkel, J. del C. (2016) *Valoracion economicade cuatro servicios ecosistémicos de la región de Chamela, Jalisco, México.* Universidad Nacional Autónoma de México.
13	Thesis	Sánchez Martínez, M. (2016) *Uso de servicios ecosistémicos en el bosque tropical seco secundario de la región Chamela-Cuixmala, Jalisco, México*. Universidad Nacional Autónoma de México.
14	Thesis	Cortés Calderón, S. V. (2017) *Oferta de servicios ecosistémicos e interacciones entre ellos en bosques tropicales secos secundarios*. Universidad Nacional Autónoma de México.
15	Thesis	Romo Díaz, G. (2016) *Conocimientos locales y científicos sobre bienes comunes en la costa sur de Jalisco: hacia la construcción de estrategias de manejo sustentable*. Universidad Nacional Autónoma de México.
16	Article	Castillo, A. *et al.* (2009) ‘El bosque tropical seco en riesgo: Conflictos enter uso agropecuario, desrrollo turistíco y provisión de servicios ecosistémicos en la costa de jalisco, de Jalisco, México’, *Interciencia*, 34(12), pp. 844–850.
17	Article	Sánchez-Azofeifa, G. A. *et al.* (2009) ‘Land cover and conservation in the area of influence of the Chamela-Cuixmala

		Biosphere Reserve, Mexico', *Forest Ecology and Management*, 258(6), pp. 907–912. doi: 10.1016/j.foreco.2008.10.030.
18	Article	Schroeder, N. M. and Castillo, A. (2013) 'Collective action in the management of a tropical dry forest ecosystem: Effects of Mexico's property rights regime', *Environmental Management*, 51(4), pp. 850–861. doi: 10.1007/s00267-012-9980-9.
19	Article	Flores-Díaz, A. C. *et al.* (2014) 'Local values and decisions: views and constraints for riparian management in western Mexico', *Knowledge and Management of Aquatic Ecosystems*, 3(414), pp. 1–19. doi: 10.1051/kmae/2014017.
20	Article	Trilleras, J. M. *et al.* (2015) 'Effects of livestock management on the supply of ecosystem services in pastures in a tropical dry region of western Mexico', *Agriculture, Ecosystems and Environment*. Elsevier B.V., 211, pp. 133–144. doi: 10.1016/j.agee.2015.06.011.
21	Article	Mora, F. *et al.* (2016) 'Trade-offs between ecosystem services and alternative pathways toward sustainability in a tropical dry forest region', *Ecology and Society*, 21(4). doi: 10.5751/ES-08691-210445.
22	Article	Gavito, M. E. *et al.* (2014) 'La vulnerabilidad del socio-ecosistema de bosque tropical seco de Chamela, Jalisco, al cambio global: un análisis de sus componentes ecológicos y sociales', *Investigación Ambiental*, 6(2), pp. 109–126.
23	Article	Ayala-Orozco, B. *et al.* (2018) 'Resilience of Soil Properties to Land-Use Change in a Tropical Dry Forest Ecosystem', *Land Degradation and Development*, 29(2), pp. 315–325. doi: 10.1002/ldr.2686.
24	Article	Lazos-Chavero, E. *et al.* (2016) 'Stakeholders and tropical reforestation: challenges, trade-offs, and strategies in dynamic environments', *Biotropica*, 48(6), pp. 900–914. doi: 10.1111/btp.12391.
25	Article	Mora, F. *et al.* (2018) 'Carbon Accumulation in Neotropical Dry Secondary Forests: The Roles of Forest Age and Tree Dominance and Diversity', *Ecosystems*, 21(3), pp. 536–550. doi: 10.1007/s10021-017-0168-2.
26	Article	Maass, M. *et al.* (2018) 'Long-term (33 years) rainfall and runoff dynamics in a tropical dry forest ecosystem in western Mexico: Management implications under extreme hydrometeorological events', *Forest Ecology and Management*, 426(July), pp. 7–17. doi: 10.1016/j.foreco.2017.09.040.
27	Article	Jimenez-Rodríguez, D. L. *et al.* (2018) 'Structural and functional

		traits predict short term response of tropical dry forests to a high intensity hurricane', *Forest Ecology and Management*. Elsevier, 426(8701), pp. 101–114. doi: 10.1016/j.foreco.2018.04.009.
28	Article	Castillo, A. *et al.* (2018) 'Linking social–ecological knowledge with rural communities in Mexico: lessons and challenges toward sustainability', *Ecosphere*, 9(10). doi: 10.1002/ecs2.2470.
29	Article	Tauro, A. *et al.* (2018) 'Unraveling heterogeneity in the importance of ecosystem services: Individual views of smallholders', *Ecology and Society*, 23(4). doi: 10.5751/ES-10457-230411.
30	Article	Flores-Casas, R. and Ortega-Huerta, M. A. (2019) 'Modelling land cover changes in the tropical dry forest surrounding the Chamela-Cuixmala biosphere reserve, Mexico', *International Journal of Remote Sensing*. Taylor & Francis, 40(18), pp. 6948–6974. doi: 10.1080/01431161.2019.1597305.

Appendix 3. List of all indicators extracted from the social-ecological literature between 2008-2019 in the Chamela-Cuixmala region. Complete list of references in Appendix 2.

			Decision-making scales			**Framework components**					
Number	**Indicator**	**Units-classes**	***Ejido***	***Ejidatario***	***Ejidal* plot**	**Ecological supply**	**Co-production**	**Benefits**	**Demand**	**Management**	**Reference**
1	N	g kg−1	0	0	1	1	0	0	0	0	22
2	Abundance per animal group	count	0	0	1	1	0	0	0	0	22
3	Access to domestic water	yes/ no	0	1	0	0	0	1	0	0	12
4	Access to electricity	yes/ no	0	1	0	0	0	1	0	0	12
5	Access to water	number of wells per cover type	0	1	1	0	1	1	0	0	13
6	Acid phosphatase activity	μg paranitrophenol g 1 dry soil h 1	0	0	1	1	0	0	0	0	22

7	Aesthetic appreciation	Relative importance: number of coins selected out of 50 total coins given	0	1	0	0	0	0	1	0	13
8	Age of ejidatarios	count	0	1	0	0	1	0	0	0	12
9	Aggregate stability	g g-1 dry soil	0	0	1	1	0	0	0	0	22
10	Amount of insecticide applied per ha	Frequency per year	1	1	1	0	1	0	0	1	5
11	Annual evapotransp iration	mm	0	0	1	1	0	0	0	0	3
12	Annual precipitation	mm	1	0	0	1	0	0	0	0	3
13	Area for cattle	ha	0	1	0	0	1	0	0	1	12
14	Areas covered with TDF in their plot	yes/no	1	1	0	1	1	0	0	0	15
15	Bacteria abundance	Nanomoles of fatty acid g^{-1} dry soil	0	0	1	1	0	0	0	0	22
16	Basal area	m2 ha-1	0	0	1	1	0	0	0	0	22
17	Biomass fodder plants	mg ha-1	0	0	1	1	0	0	0	0	25
18	Biomass woody plants	mg ha-1	0	0	1	1	0	0	0	0	25
19	Bulk density	g cm-3	0	0	1	1	0	0	0	0	22
20	Burning to pasture frequency	number of times/year * number of years of management	1	1	1	0	1	0	0	1	5
21	Burning to pasture surface	ha	1	1	1	0	1	0	0	1	5

22	C stock	ton/ha	0	0	1	1	0	0	0	0	14
23	Capacity of water sources	number of cattle supplied by each source	0	1	0	0	1	1	0	0	13
24	carbon concentratio n	mg/g	0	0	1	1	0	0	0	0	22
25	Carbon sequestratio n	ton/ha/year	0	0	1	1	0	0	0	0	14
26	Cattle ownership	yes/no	1	1	0	0	1	1	0	0	15
27	Cattle surface	ha	1	1	1	0	1	0	0	1	5
28	Cattle water needs (dry season)	number of drinking times/day	0	1	0	0	1	1	0	0	13
29	Cattle water needs (wet season)	number of drinking times/day	0	1	0	0	1	1	0	0	13
30	Clearing to pasture frequency	number of times/year * number of years of management	1	1	1	0	1	0	0	1	5
31	Clearing to pasture surface	ha	1	1	1	0	1	0	0	1	5
32	Clearing tool	Manual/Machine/An imals/Other	1	1	1	0	1	0	0	0	5
33	Community weighted variances (CWV) of functional traits	Index	0	0	1	1	0	0	0	0	25
34	cost of forest products extraction	labor/year	0	1	1	0	1	0	0	0	12
35	Distance to the road	km	0	0	1	0	1	0	0	0	7

36	Distance to the villages	m	0	0	1	0	1	0	0	0	7
37	Cover per vegetation type	%	1	0	1	1	0	0	0	0	3
38	Cropping frequency	number of times/year * number of years of management	1	1	1	0	1	0	0	1	5
39	Cropping surface	ha	1	1	1	0	1	0	0	1	5
40	Crops ownership	yes/no	1	1	0	0	1	1	0	0	15
41	Crops problems	yes/no	1	1	0	0	0	1	0	0	15
42	Density of trees	Number ha -1	0	0	1	1	0	0	0	0	22
43	Distance to the CCBR	km	0	0	1	0	1	0	0	1	30
44	Diversity of productive activities	yes/no	0	1	0	0	0	1	0	0	29
45	Domestic water source	water well, municipal water system, river, spring, waterhole, other	1	1	0	0	0	1	0	0	15
46	Duration of clearing	Number of years doing clearing	1	1	1	0	1	0	0	1	5
47	Duration of roza-tumba-quema	Number of years doing roza-tumba-quema	1	1	1	0	1	0	0	1	5
48	Duration of weeding	Number of years doing weeding	1	1	1	0	1	0	0	1	5
49	Economic valuation carbon sink	USD ha−1yr−1	0	1	1	0	0	0	1	0	12
50	Economic valuation carbon stock	USD ha−1	0	1	1	0	0	0	1	0	12

51	Economic valuation fodder	USD/ha/year Precio del mercado o valoración contingente	0	1	1	0	0	0	1	0	12
52	Economic valuation forest products	USD/ha/year Precio del mercado o valoración contingente	0	1	1	0	0	0	1	0	12
53	Economically active population at 2010 per locality	%	1	0	0	0	1	0	0	0	12
54	Edible products extraction	kg extracted per cover type	0	1	0	1	1	1	0	0	13
55	Edible products extraction effort	days/year	0	1	0	0	1	1	0	0	13
56	Education level of ejidatarios	none, elementary school, higher education	0	1	0	0	1	0	0	0	12
57	Ejidal plot surface	ha	1	1	1	1	1	1	0	1	13
58	Ejidatarios type	socioeconomic categories	0	1	0	0	1	0	0	0	12
59	Ejido of ejidatario	Name of Ejido	0	1	0	0	1	0	0	0	29
60	Ejido´s surface	ha	1	0	0	0	0	0	0	1	16
61	Elevation	m	1	0	1	1	0	0	0	0	30
62	Environmental deterioration degree	Index	1	0	0	1	0	0	0	0	3
63	Fodder potential supply	% underwood coverage	0	0	1	1	0	0	0	0	14
64	Fodder species	spp	0	1	0	0	1	0	0	0	13

65	Forest clearing frequency	number of times/year * number of years of management	1	1	1	0	1	0	0	1	5
66	Forest clearing surface	ha	1	1	1	0	1	0	0	1	5
67	Forest species as fodder	yes/no	1	1	0	1	1	0	1	0	15
68	Forest successional state	pasture/early successional forest, advanced successional forest, mature forest	0	0	1	1	1	0	0	0	14
69	Frequency of cropping per year	count	1	1	1	0	1	1	0	1	5
70	Frequency of forest clearing for cattle	count	1	1	1	0	1	0	0	1	5
71	Frequency of forest clearing for cropping	count	1	1	1	0	1	0	0	1	5
72	Frequency of roza-tumba-quema per year	count	1	1	1	0	1	0	0	1	5
73	Frequency of timber extraction per year	count	1	1	1	0	1	1	0	1	5
74	Fungal abundance	Nanomoles of fatty acid g 1 dry soil	0	0	1	1	0	0	0	0	22
75	Grazing frequency	number of times/year * number of years of management	1	1	1	0	1	0	0	1	5
76	Grazing surface	ha	1	1	1	0	1	0	0	1	5

77	Health expenses	none, public service, private service	0	1	0	0	0	1	0	0	12
78	Hidrogeologic units	pasture/early hidrogeologic, advanced Hidrogeologic, mature hidrogeologic	1	0	0	1	0	0	0	0	3
79	Huizache presence in the plot	yes/no	1	1	0	0	0	1	0	0	15
80	Hunting effort	days/year	0	1	0	0	1	1	0	0	13
81	Hunting specimens	number of animals/coverture type	0	1	0	1	1	1	0	0	13
82	Importance Value Index	0-1	0	1	0	0	0	0	1	0	29
83	Intra-annual droughts	canículas per year	1	0	0	1	0	0	0	0	26
84	Knowledge about reproduction of trees	count	1	1	0	0	1	0	1	0	28
85	Land use cover	% o ha	0	0	1	1	0	0	0	0	21
86	Life appreciation	Relative importance per cover type: number of coins selected out of 50 total coins given.	0	1	0	0	0	0	1	0	13
87	Litter	Mg C ha 1	0	0	1	1	0	0	0	0	22
88	Long-term view of the plot management	count	0	1	0	0	1	0	0	0	5
89	Management of huizache	burning, elimination, fodder, other	1	1	0	0	1	0	0	0	15
90	Management	count	0	1	0	0	1	0	0	0	5

	recomendations ejidatario to ejidatario										
91	management strategies in silvopastoral plots	count	1	1	0	0	1	1	0	0	15
92	Measures against soil erosion	count	1	1	0	0	1	0	0	0	15
93	Monthly precipitation	mm	1	0	0	1	0	0	0	0	3, 26
94	Months of the crop cycle	month names	1	1	1	0	1	0	0	0	15
95	Number of agricultural management years	count	1	1	1	0	1	0	0	1	5
96	Number of cattle per ha	count	1	1	1	0	1	1	0	1	5
97	Number of cattle selled per year	count	0	1	0	0	1	1	1	0	12
98	Number of clearings per crop cycle	count	1	1	1	0	1	0	0	1	5
99	Number of dependents	count	0	1	0	0	1	0	0	0	12
100	Number of ejidatarios living in the ejido	count	1	0	0	0	1	0	0	0	5
101	Number of ejidatarios that left areas covered with TDF in their plot	count	1	1	0	0	1	0	0	0	28

102	Number of fodder species	count	0	0	1	1	0	1	0	0	13
103	Number of habitants per locality	count	1	0	0	0	1	0	0	0	3
104	Number of hired labor	Number of people hired	0	1	0	0	1	0	0	0	29, 12
105	Number of hours cattle spent in the shadow per day	count	0	0	1	0	1	0	0	1	13
106	Number of income sources	count	0	1	0	0	1	1	0	0	12
107	Time of livestock managemen t	no. Years with cattle	1	1	1	0	1	1	0	1	5
108	Number of managemen t years	years since first tillage	1	1	1	0	1	0	0	1	5
109	Number of months cattle stay in the plot per year	count	1	1	1	0	1	0	0	1	5
110	Number of owned plots per ejidatario	count	0	1	0	0	1	1	0	0	13
111	Number of perceived benefits of the riparian system per ejidatario	count	0	1	0	0	1	1	0	0	19
112	Number of perceived riparian species per ejidatario	count	0	1	0	0	1	0	0	0	19
113	Number of received	count	0	1	0	0	1	0	0	0	12

	support programs										
114	Number of recurrence of the same crop	count	1	1	1	0	1	0	0	1	5
115	Number of roza-tumba-quema in the plot since the beggining of use	count	1	1	1	0	1	0	0	1	5
116	Number of sons who help in the plot	count	0	1	0	0	1	0	0	0	29, 12
117	Number of unmanagem ent years	years since last tillage	1	1	1	0	1	0	0	1	5
118	Number of usefull tree species identified per ejidatario	count	0	0	0	1	1	1	1	0	28
119	Number of users of ground water	Number of habitants per locality	1	0	0	0	0	1	1	0	3
120	Number of years of cropping in the plot	count	1	1	1	0	1	0	0	1	5
121	Number of years of pasture seeding	Years with seeding pasture in the plot	1	1	1	0	1	1	0	1	5
122	Number of years since Ejido creation	count	1	0	0	0	1	0	0	1	16
123	Number of years since herbicide application	count	1	1	1	0	1	0	0	1	5

124	Number of years since last wood management intervention	years since last timber extraction	1	1	1	0	1	0	0	1	5
125	Number of years with management in the plot	count	0	0	1	1	1	0	0	1	21, 12
126	Number of years since NOT burning for pasture	count	1	1	1	0	1	0	0	1	5
127	Number of years since NOT clearing for pastures	count	1	1	1	0	1	0	0	1	5
128	Number of years since NOT cropping	count	1	1	1	0	1	0	0	1	5
129	Number of years since NOT forest clearing	count	1	1	1	0	1	0	0	1	5
130	Number of years since NOT grazing	count	1	1	1	0	1	0	0	1	5
131	Number of years since NOT pastures	count	1	1	1	0	1	0	0	1	5
132	Number of years since NOT roza-tumba-quema	count	1	1	1	0	1	0	0	1	5
133	Number of years since NOT timber extraction	count	1	1	1	0	1	0	0	1	5

134	Number of years since NOT weeding	count	1	1	1	0	1	0	0	1	5
135	Number of years since NOT wood extraction	count	1	1	1	0	1	0	0	1	5
136	Number of years since NOT yardstick for tomato extraction	count	1	1	1	0	1	0	0	1	5
137	Number of years since roza-tumba-quema	count	1	1	1	0	1	0	0	1	5
138	Number of years since timber extraction	count	1	1	1	0	1	0	0	1	5
139	Number of years since wood extraction	count	1	1	1	0	1	0	0	1	5
140	Number of years since yardstick for tomato extraction	count	1	1	1	0	1	0	0	1	5
141	Number of years with clearing to pastures	count	1	1	1	0	1	0	0	1	5
142	Number of years with grazing	count	1	1	1	0	1	0	0	1	5
143	Number of years with pasture	count	1	1	1	0	1	0	0	1	5
144	Number of years with weeding	count	1	1	1	0	1	0	0	1	5

145	organic carbon	g kg−1	0	0	1	1	0	0	0	0	3
146	Aspect degree (orientation)	degrees	1	0	1	1	0	0	0	0	30
147	P total	g kg−1	0	0	1	1	0	0	0	0	22
148	Participation in conservation programs	types of programs	1	1	0	0	1	0	0	0	15
149	Pasture frequency	number of pasture times/year * number of years of management	1	1	1	0	1	0	0	1	5
150	Pasture species cover	% per specie	0	1	0	1	1	0	0	0	13
151	Pasture surface	ha	1	1	1	0	1	0	0	1	5
152	Perceived change of the stream in the last 30 years	number of mentions of ideas expressed by interviwees	0	1	0	0	1	0	1	0	19
153	Percentage per cover type	%	1	1	1	1	1	1	0	1	13
154	perception of the proportion of their land that is still covered with Tropical DRy Forest	%	0	1	0	0	1	0	1	0	17
155	perception of usefulness of scientific booklets given to stakeholders	Useful/Clear and easy/entertaining/attractive. Agree-Disagree-Indifferent	0	1	0	0	1	0	0	0	28

156	Perceptions of own health	good/bad	0	1	0	0	0	1	1	0	12
157	Perceptions of restoration programs	% of frequency of opinions from interviews	0	1	0	0	1	0	1	0	5
158	Perceptions of soil change	% of frequency of opinions from interviews	0	1	0	0	1	0	1	0	5
159	Perceptions of vegetation change	% of frequency of opinions from interviews	0	1	0	0	1	0	1	0	5
160	Place of work same as ejidatario´s residence	yes/no	1	1	0	0	1	0	0	0	29, 5
161	Plants extraction	spp	1	1	1	1	1	0	0	1	5
162	Plot type	pasture/agriculture/early succession forest/advanced succession/mature forest	0	0	1	1	1	0	0	0	13
163	Plots in silvopastoral systems	yes/no	1	1	0	0	1	1	0	0	15
164	Potential supply of multiple resources	m2 ha-1	0	0	1	1	0	0	0	0	14
165	Potential transition values	% rate of change	1	0	0	1	0	0	0	1	30
166	Preference of use	%	1	1	0	0	1	0	1	0	15
167	Presence of artificail water bodies	water ditch, font, tanks, artificial small lakes, others	1	1	0	0	1	1	0	0	15
168	Priority of trees	frequency per tree species	0	1	0	0	0	0	1	0	28

169	Problems in plant reproduction	cost/plagues//growth/drought/other	1	1	0	0	0	1	0	0	15
170	Problems to stock water	lack of infraestructure/evaporation/other	1	1	0	0	1	1	0	0	15
171	quantity of forest products extracted	kg of wood	0	1	0	0	1	1	0	1	12
172	Quantity of herbicide applied per ha per year	lt	1	1	1	0	1	0	0	1	5
173	Rain Erosivity	Fournier index	0	0	1	1	0	0	0	0	3
174	rainfall duration	time	1	0	1	1	0	0	0	0	26
175	Rainfall frequency	frequency of precipitations per year	1	0	1	1	0	0	0	0	26
176	rainfall intensity	mm h−1	1	0	0	1	0	0	0	0	26
177	Received support programs	none, social, productive, productive-social	0	1	0	0	1	0	0	0	29
178	Recreational walks in the pastures	yes/no	0	1	0	0	0	0	1	0	13
179	Relation to the Biological Station	Distant, Medium, Close	0	1	0	0	1	0	0	0	29
180	Preferences of trees	spp	1	1	0	1	1	0	1	0	15
181	Remittances	yes/no	0	1	0	0	1	0	0	0	29, 12
182	Resting period of the cropping land	Number of resting months	1	1	1	0	1	0	0	1	5

183	Richness of herbaceous vegetation	rarefaction of observed herbaceous spp	0	0	1	1	0	0	0	0	22
184	Richness of woody vegetation	rarefaction of observed tree spp	0	0	1	1	0	0	0	0	25, 21
185	Root mass	Mg C ha-1	0	0	1	1	0	0	0	0	25
186	Rotating pastures	yes/no	1	1	1	0	1	1	0	1	5
187	Roza-tumba-quema intensity	number of times/year * number of years of management	1	1	1	0	1	0	0	1	5
188	Roza-tumba-quema surface	ha	1	1	1	0	1	0	0	1	5
189	runoff depth	mm	1	0	0	1	0	0	0	0	26
190	Sediment yield	kg ha−1 y−1	1	0	0	1	0	0	0	0	26
191	selective cutting	yes/no	1	1	0	0	1	1	0	0	15
192	Sense of heritage of pastures	Relative importance per cover type: number of coins selected out of 50 total coins given.	0	1	0	0	0	0	1	0	13
193	Sense of identity	Relative importance per cover type: number of coins selected out of 50 total coins given.	0	1	0	0	0	0	1	0	13
194	Sense of peace	Relative importance per cover type: number of coins selected out of 50 total coins given.	0	1	0	0	0	0	1	0	13
195	Sense of well being	Relative importance per cover type: number of coins selected out of 50 total coins given.	0	1	0	0	0	0	1	0	13

196	Silage fodder stock	kg	0	1	0	0	1	0	0	0	13
197	Slope	degrees	0	0	1	1	0	0	0	0	3
198	Soil compaction	Soil bulk density (g cm3)	0	0	1	1	0	0	0	0	22
199	Soil depth	cm	0	0	1	1	0	0	0	0	3
200	Soil erodability	% of the nomogram of the USDA	0	0	1	1	0	0	0	0	3
201	Soil permeability	Low/medium/high	0	0	1	1	0	0	0	0	3
202	Soil pH	count	0	0	1	1	0	0	0	0	22
203	Soil type	Cambisol/Leptosol/ Vertisol/Regosol	0	0	1	1	0	0	0	0	3
204	strategy for obtaining seeds	trees/nurseries	1	1	0	0	1	0	0	0	28, 15
205	strategy for seed stock	in sacks, glass jars, paper bags, I do not store, other	1	1	0	0	1	0	0	0	15
206	Technical support received	yes/no	1	1	0	0	1	0	0	0	15
207	Tillage tool	Manual/Machine/Animals/Other	1	1	1	0	1	0	0	0	5
208	Timber extraction	Number of extraction times/year, number of poles extracted per cover type	1	1	1	1	1	1	0	1	5, 13
209	Timber extraction area	ha	1	1	1	0	1	0	0	1	5
210	Timber extraction effort	number of timber extraction per year, days per year	1	1	1	0	1	1	0	1	5, 13
211	Timber extraction frequency	number of times/year * number of years of management	1	1	1	0	1	0	0	1	5

212	Timber for cooking	yes/no	1	1	1	0	0	1	0	0	5
213	Timber selling price	USD/kg	0	1	1	0	0	0	1	0	12
214	Timber tool	machete/axe/chainsa w	1	1	1	0	1	0	0	0	5
215	Time spent of cattle per cover type	Relative time	0	1	1	1	1	0	0	1	13
216	Treatment for seeds germination	yes/no	1	1	0	0	1	0	0	0	15
217	Tree plantations	yes/no	1	1	0	0	1	1	0	0	15
218	Tree shade	count	0	0	1	1	0	0	0	0	13
219	Tree species in plantations	count	1	1	0	1	0	0	1	0	15
220	Type of fuel	wood/gas	0	1	0	0	1	1	0	0	12
221	Type of herbicide applied	herbicides names	1	1	1	0	1	0	0	0	5
222	Type of managemen t of riparian area per benefit	12 management types	0	1	0	0	1	0	0	0	19
223	Use of herbicide	yes/no	1	1	1	0	1	0	0	1	5
224	Use of insecticide	yes/no	1	1	1	0	1	0	0	1	5
225	Use of tree species	vara, others, none	1	1	0	0	0	0	1	0	15
226	Vegetation dominance	J Pielou spp. Eveness index	0	0	1	1	0	0	0	0	25
227	Vegetation type	Agriculture/tropical forest/ template forest/pasture	1	0	0	1	0	0	0	0	3

228	Water infiltration	High/medium/low	1	0	0	1	0	0	0	0	3
229	Water sources to cattle	count	0	1	0	0	1	1	0	0	13
230	water stock	yes/no	1	1	0	0	1	1	0	0	15
231	Water supply available	yes/no	0	1	0	1	0	0	0	0	3
232	Weeding frequency	number of times/year * number of years of management	1	1	1	0	1	0	0	1	5
233	Weeding surface	ha	1	1	1	0	1	0	0	1	5
234	who can access the riparian area	stakeholders types	0	1	0	0	1	0	0	0	19
235	Willing to participate in a conservation program	yes/no	1	1	0	0	1	0	0	0	15, 5
236	Wood extraction	kg extracted per cover type	1	1	1	1	1	1	0	0	13
237	Wood extraction area	m2	1	1	1	0	1	0	0	1	5
238	Wood extraction effort	Number of wood extraction per year, days per year	1	1	1	0	1	1	0	1	5, 13
239	Wood extraction frequency	number of times/year * number of years of management	1	1	1	0	1	0	0	1	5
240	Wood extraction surface	ha	1	1	1	0	1	0	0	1	5
241	Wood for cooking	yes/no	1	1	1	0	1	0	0	0	5

242	wood species	spp	1	1	1	1	1	0	0	0	5
243	Wood tool	machete/axe/chainsaw	1	1	1	0	1	0	0	0	5
244	Yardstick for tomato extraction frequency	number of times/year * number of years of management	1	1	1	0	1	0	0	1	5
245	Yardstick for tomato extraction surface	ha	1	1	1	0	1	0	0	1	5

Appendix 4. Subcomponents full description

Ecological supply, we propose to use the Essential Biodiversity Variables (EBV, Pereira et al. 2013) as subcomponents of analysis. It includes ecosystem structure, ecosystem species and ecosystem function.

Ecosystem structure- Static or slow change components from Nature (i.e. Habitat structure, ecosystem composition).

Species population- Biodiversity indicators (i.e. Species distribution, abundance, richness).

Ecosystem function- Dynamic fast components part of different processes (i.e. Net primary productivity, disturbance intensity).

Co-production, we propose to follow the subcomponents proposed by Palomo et al. 2016 to analyze this component. The subcomponents of analysis are the human capital, social capital, financial capital, and manufactured capital.

Social capital- intangible assets associated with formal and informal networks that facilitate mutual benefit (i.e. trust, shared values, and norms).

Human capital- personal attributes embodied in the ability to perform labor. It comprises people's health, knowledge, education, skills, and motivations.

Manufactured capital- Fixed physical assets that contribute to the production or process of goods and services (i.e. tools, machines, infrastructures, built capital)

Financial capital- Financial resources invested to produce NCP (i.e. Savings, credits, money).

Management, we propose to analyze this component by the subcomponents proposed by Trilleras et al. 2015, Zermeño-Hernández et al. 2015, and Pérez-Cárdenas, 2020, being time of management, intensity and extension.

Time- years of land use with productive purposes

Intensity- management regime variables limited to the number of cattle per year, frequency of fire incidence, and chemical use.

Extension- number of hectares under the management regime

Demand: use and values subcomponent of analysis are the instrumental values, the relational values, and the priorities of use (Chan et al. 2016; Pascual et al. 2017; Arias-Arévalo et al. 2017).

Instrumental values- Worth based on means to an end, object´s values or what satisfies people (i. e. economic value of nature, the demand of water, fodder species).

Relational values- Preferences, principles, virtues about/based on meaning-saturated relationships. Values based on contributions to a good quality of life (i.e. cultural identity, social cohesion, residing time in a place).

Priorities of use-Demand and use of NCP (i.e. the most rentable species, timber species, use of timber).

Benefits from Nature´s Contributions to People, we propose to follow as subcomponents of analysis the variables proposed by the Millennium Ecosystem Assessment (MA 2005), and the IPBES Europe and Central Asia report (IPBES, 2018, ECA report): good social relationships, good health, livelihood security, energy security, food security, and water security.

Good social relationships- How strong is the social network (i.e. how many people they trust)

Good health- Access to health services

Livelihood security- Diversity of activities for income to secure revenues. Access and use of NCP (i.e. Number of cattle, income strategy, number of income activities).

Energy security- access to energy (e.g. Electric services at home)

Food security- access to food (e.g. Number of cattle, problems with livestock/ crop production)

Water security- access to water (e.g. Demand of water, source of water)

CHAPTER III. SPATIAL CHARACTERIZATION OF SOCIAL-ECOLOGICAL SYSTEMS UNITS FOR MANAGEMENT IN TROPICAL DRY FORESTS

"Friendship evenings"   Patricia Santillán Carvantes. August 2021

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RESEARCH ARTICLE

Spatial characterization of social-ecological systems units for management in Tropical Dry Forests

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Abstract
Context Understanding the complex interdependencies between nature and people is a major challenge for the sustainable management of social-ecological systems. Spatially explicit identification of these interdependencies is particularly relevant for managing biodiversity hotspots, such as Tropical Dry Forests (TDF).

Objectives We provided a methodology to spatially identify the components of social-ecological systems that have been shaped by both environmental conditions and management practices at three relevant decision-making scales: plots owned by individuals, plot owners, and governance units. To do so, we identified and characterized: (1) ecological clusters (EC), (2) social-management clusters (SC), and (3) social-ecological systems units (SESU) in a TDF in western Mexico.

Methods We used multivariate analysis to identify and characterize the ECs, SCs, and SESU at the respective decision-making scales.

Results We found four EC, SC, and SESU clusters. Differences between ECs were based on their elevation and land cover type. The SC differed according to the management intensity of cattle and forests. Differences between SESU were based on land management regime (individual vs collective), plot sizes, and time under private schemes.

Conclusions Our findings suggested that decision-makers (*ejidatarios*) are bounded by the topographical characteristics and the public policies that determine communal (or private) governance, also by the number of resources available to them. The methodology can be applied to other contexts and nested decision-making scales. The spatial identification of these interdependencies is critical for landscape planning since it can contribute to reconciling productive activities and biodiversity conservation.

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Introduction

Tropical dry forests (TDF) are important biodiversity hotspot areas and the second-largest tropical forest in Latin America (Quijas et al. 2019). A close historical relationship between human settlements and TDF use has led to the conversion of approximately 80% of the original TDF surface into pastures for cattle ranching and agricultural activities (Balvanera et al. 2011; Dirzo 2011; Gavito et al. 2014). Growing efforts have taken place to monitor and understand the social-ecological dynamics in these forests (Mastrangelo and Laterra 2015; Quijas et al. 2019; Jara-Guerrero et al. 2019). Exemplary social-ecological dynamics in TDF include ecosystem services provided to society (Maass et al. 2005), ecosystem services contribution to human well-being (Tauro et al. 2018), management strategies that guarantee the sustainable provision of ecosystem services (Mastrangelo and Laterra 2015; Trilleras et al. 2015; Monroy-Sais et al. 2020; Sánchez-Romero et al. 2021), and the successional dynamics of the forest recovery (Jara-Guerrero et al. 2019; Gavito et al. 2021; Cortés-Calderón et al. 2021; Pérez-Cárdenas et al. 2021). However, the concept of social-ecological systems (SES; Berkes et al. 1998; Ostrom 2009) is underexplored as a means to understand the complex interactions of social-ecological systems in TDFs.

A challenge to spatially identifying social-ecological units is the nested and hierarchical nature of social and biophysical components, which underpin management decisions (Hanspach et al. 2016; Martín-López et al. 2017; Lazzari et al. 2019) in response to local people's needs (Castillo et al. 2018). Social factors, which are embedded and driven by culture, politics, economics, and governance across scales (Chapin et al. 2009; Martín-López et al. 2017), determine the conditions in which people manage the land. Therefore, identification of social-ecological units (sensu Martín-López et al. 2017) entails understanding the interactions between the social and ecological factors that affect decision-making (Cumming et al. 2005; Virapongse et al. 2016). However, scales at which ecological and social data are collected do not correspond to the scales at which people make land management decisions. Among the few studies have spatially characterized social-ecological systems in land and seascapes (e.g. Martín-López et al. 2017; Lazzari et al. 2019; Pacheco-Romero et al. 2020); efforts to do so in TDFs have already started (Monroy-Sais et al. 2020; Sánchez-Romero et al. 2021). However, incorporating the minimum local governance level and decision-making scales remains a methodological challenge.

The goal of this study was to provide a methodological approach to identify and characterize the components of social-ecological system units at three relevant decision-making scales. Specifically, we: (1) identified ecological clusters (EC) at the plot scale, (2) identified social-management clusters (SC) at the plot owner scale, and (3) spatially characterized the social-ecological system units (SESU) within the landscape at the smallest governance unit scale. We discussed how ecological-social interlinkages determine current landscape configuration in the western TDF in Mexico. We then explored how this methodological approach can contribute to the identification of opportunities to reconcile productive activities and biodiversity conservation.

Methods

Study area

The Chamela-Cuixmala region is part of the TDF biome located along the Mexican Pacific coast (Ceballos and García 2010). It is a biodiversity hotspot area where a Long Term Social-Ecological Research network has been working for almost three decades (Maass et al. 2005; Castillo et al. 2018; Balvanera et al. 2021). The region comprises the Chamela-Cuixmala Biosphere Reserve and its transition area (UNESCO 2022), located in the municipalities of La Huerta and Villa Purificación in the state of Jalisco, Mexico (Fig. 1). Topography is dominated by hills between 20 and 180 m, although some flatlands occur in floodplains and valleys along the main rivers and seasonal streams (Cotler and Ortega-Larrocea 2006). Soils on hills are poorly developed, predominated by entisols with sandy loams in texture (Cotler and Ortega-Larrocea 2006). Rainfall is seasonal with an annual mean of 800 mm, concentrated between

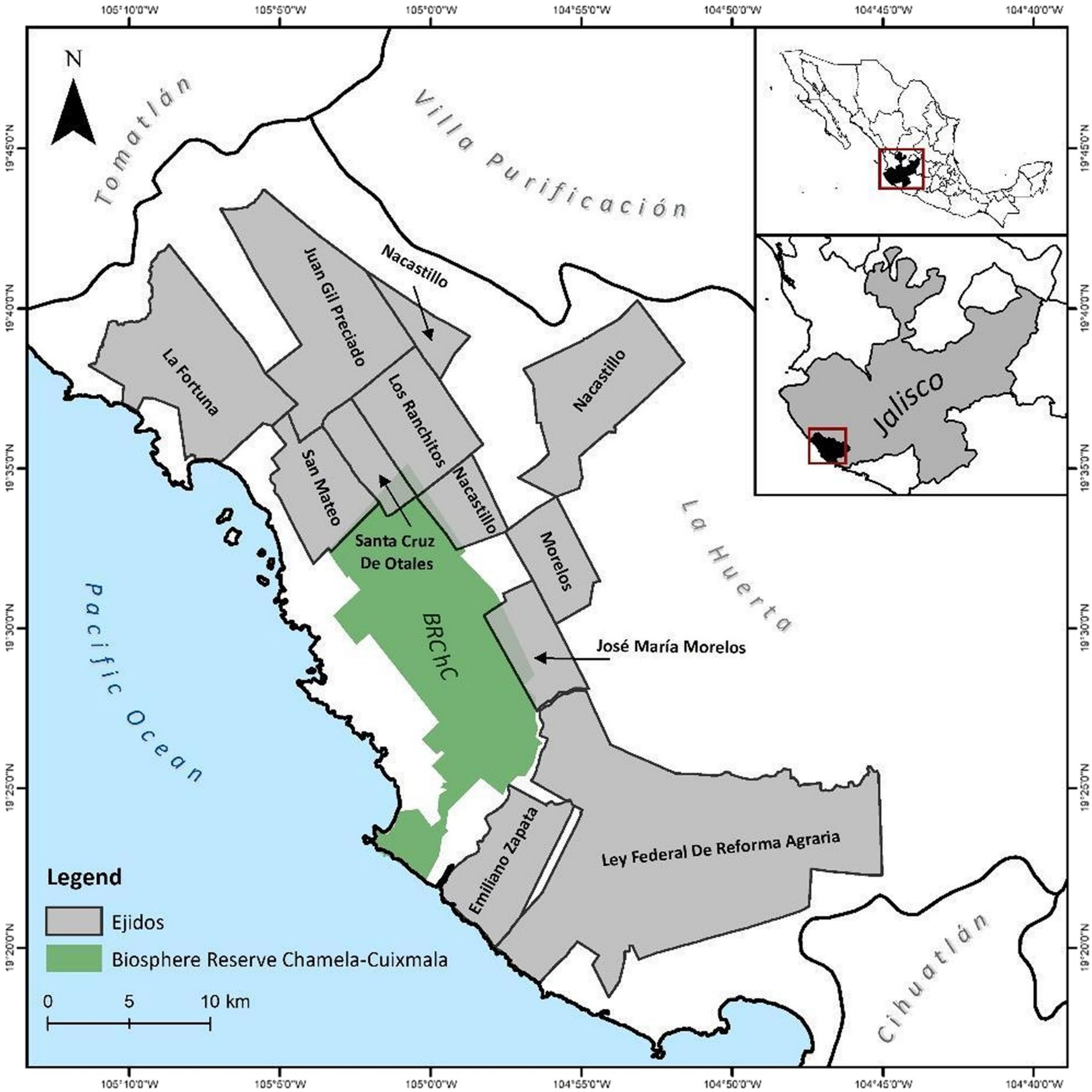

Fig. 1 Location of the Chamela-Cuixmala region, comprised of the Biosphere Reserve Chamela-Cuixmala (BRChC; green color) and the transition areas at the governance units (*ejidos*; grey color) in the adjacent area, in the Municipality of La Huerta and Villa Purificación, Jalisco, Mexico

June and October (Maass et al. 2018). The mean annual temperature is 25.6 °C (1980–2015), with a monthly minimum and maximum of 16.4 °C and 32.6 °C respectively (Maass et al. 2018).

Biosphere reserves have core, buffer, and transition areas with different protection and restriction levels that foster social-ecological sustainable activities; therefore this region is mainly covered by TDF in different successional stages and patches (Sánchez-Azofeifa et al. 2009; Flores-Casas and Ortega-Huerta 2019). Within the reserve, most of the forest is old-growth with no signs of human intervention in recent decades. In the surroundings, the region has undergone extensive land-use change in the last five decades, mainly to crop fields in flatlands and induced pastures for cattle grazing on hills. Pastures

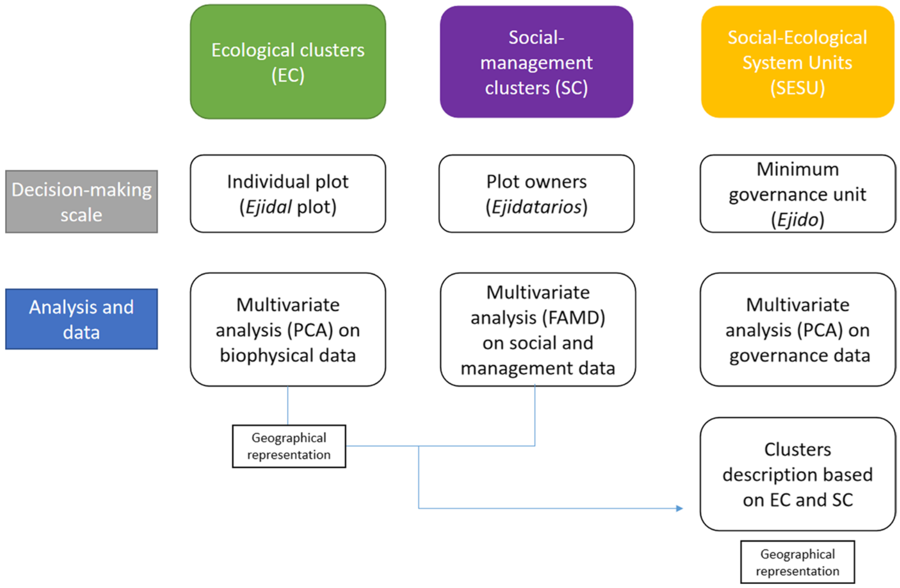

Fig. 2 The methodological approach used to spatially identify the Social-Ecological Systems Units (SESU). *PCA* principal component analysis. *FAMD* factorial analysis of mixed data. *Ejidal* plots are owned by the *ejidatarios*, who have legal rights to inherit and sell the land, as well as vote in the Assembly for making decisions on the communal areas. *Ejidos* are semi-communal land tenures with private and communal lands

are burned to reduce woody species and foster pasture growth, which leads to nutrient depletion and long-term reduction in forage quality (Burgos and Maass 2004; Trilleras et al. 2015). These lands are sometimes left unmanaged, allowing the forest to regrow. As a result, the landscape outside the reserve is a mosaic of grassland patches, secondary forests, and old-growth forests (Sánchez-Azofeifa et al. 2009; Flores-Casas and Ortega-Huerta 2019).

The ownership regime is a critical factor that affects the landscape configuration in the transition areas. Most of the land (70–80%) is under a governance unit specific to Mexico, called *ejido*, a semi-communal land tenure regime that emerged from the land redistribution policies following the Mexican Revolution of the 1910s (Castillo et al. 2005; Monroy-Sais et al. 2020; Fig. 2). Local collective management arrangements have been developed in many *ejidos*, and are operationalized through an *ejidal* assembly (Toledo 1996; Agrawal 2007; Schroeder and Castillo 2013). In the Chamela-Cuixmala region, *ejido* formation occurred between 1950 and 1975 and was linked to a governmental program called "March to the sea" ("Marcha al mar"), designed to colonize uninhabited and isolated coasts and to promote tourism (Castillo et al. 2005; Lazos-Chavero et al. 2016). Today, the region comprises the Chamela-Cuixmala Biosphere Reserve core area, the buffer area that corresponds to some lands surrounding the southern area of the reserve (Ceballos et al. 1999), including private ecotouristic alternatives from private owners, and the transition area that includes five small towns (Careyes, Cuixmala, Zapata, Villa, Chamela), eight *ejidos* in the Biosphere Reserve boundaries, and three tourist developments (Costa Cuixmala, Club Med, Careyes) (Ceballos et al. 1999; Sánchez-Azofeifa et al. 2009). In this study, we focused on seven of the eight *ejidos* in the transition area, plus two more in the contiguous area of the Northern part where farming activities and forest land cover are highly represented (Fig. 1).

Land rights within *ejidos* in this region can take place in three different ways (Schroeder and Castillo 2013). First, *ejidatarios*, or the landholding members of the *ejido*, can inherit the land right (*ejidal* plots), sell it, and vote in the *ejidal* assembly to take communal decisions. *Ejidatarios* have rights over communal lands within the *ejido*. Second, *posesionarios* possess land within the *ejido* but cannot pass it to the following generation. *Posesionarios* do not hold rights over communal lands and cannot vote in the *ejidal* assembly. Each *ejido* determines the level of *posesionarios* participation in collective management. Finally, *avecindados* are those who have settled within the *ejido* for more than a year, and neither possesses land rights nor vote in the Assembly. Traditionally, men hold most of these three types of land rights and make land-related decisions; although there are few "*ejidatarias*" (women).

Ejidatarios within *ejidos* surrounding the Chamela-Cuixmala Biosphere Reserve are aligned with the extensive cattle ranching and silvopastoral culture (Tauro et al. 2021). Cattle ranching is strongly limited by biophysical aspects such as water availability, as well as economic aspects such as financial resources to invest in cattle maintenance (Maass et al. 2005). There have been identified three different types of *ejidatarios* in the area; the first one includes *ejidatarios* with a high financial income that own larger extensions of land and cattle. They have better means to fulfil their livelihood needs. The second group is comprised of *ejidatarios* with lower education and are highly dependent on cattle activities. The third group is *ejidatarios*, which have a diversity of productive activities and a high number of plot areas (Naime Sánchez Henkel 2016). Emigration in the area has resulted in a lack of young producers and many abandoned areas (Cohen-Salgado 2014; Torales-Ayala 2015). Traditionally in the region, a strong emphasis on biodiversity conservation has excluded the local communities and neglected their needs, particularly *ejidatarios* surrounding the Biosphere Reserve (deeper historical explanation in Supplementary information 1). This has led to a general rejection of the Biosphere Reserve and conservation activities (Castillo et al. 2018).

Methodological approach

Our methodology was adapted from Martín-López et al. (2017), and structured in three phases (Fig. 2) that align with our objectives (see above). Social-ecological dynamics are the result of interconnection among three decision-making scales (Supplementary information 2).

For our study site, we characterized homogeneous spatial clusters based on topography, soil information, and landscape ecological conditions. We used the *ejidal* plot (individual plot) as the unit of ecological analysis since it is the minimum decision-making spatial scale. Then, we characterized clusters of *ejidatarios* (the plot owners) based on similar social and management decisions. Finally, we identified social-ecological system units at the *ejido* scale (minimum governance unit) based on the governance and infrastructure connectivity context at the landscape level, where we described the existing relations between the ecological and social-management clusters. We relied on available data on ecological, social, and management decisions as well as on governance dynamics (Table 1).

Data sources

Individual plots: We selected 63 *ejidal* plots (7–30 ha) for this study. The first 30 were randomly selected to cover: (i) a range of land cover and topographic landscape composition patterns; (ii) heterogeneous land use intensity; and (iii) geographic dispersion across the *ejidos* surrounding the reserve (Pérez-Cárdenas et al. 2021). The remaining 33 were randomly selected to represent variation in the stand age and structure of TDF across the hilly region (Mora et al. 2018). We also used soil data available for a subset of these (Supplementary information 3). The georeferenced location of each plot was used to identify the corresponding polygon reported by the Mexican Agrarian Record "Registro Agrario Nacional" (RAN 2022). For 26 plots for which polygon data were missing, a polygon with an area equal to the median area size of the plots across the region (~25 hectares) was simulated. Polygons for which no ecological data were available (n = 1757) were excluded. In the case of two or more points located within the same polygon (*ejidal* plot), we calculated the average value for each quantitative variable among all the points within the plot. The 63 plots assessed here included different successional forest stages, and represent 3.5% of the existing *ejidal* plots (n = 1820). For each plot, we calculated nine topographical variables using data from the Shuttle Radar Topography Mission (SRTM) (Farr 2000) in Google Earth Engine (Gorelick et al. 2017; Tables 1, S.1).

Plot owners: We focused on 67 *ejidatarios* who participated in previous studies and for whom management data were available (Cohen-Salgado 2014; Mora et al. 2018; Pérez-Cárdenas et al. 2021, Ramírez-Ramírez unpublished data). These *ejidatarios* were selected to maximize the representation of different *ejidal* plot successional stages and by financial resources and educational level. There are at least three *ejidatarios* per *ejido*, covering *ejidatarios* from the nine *ejidos* surrounding the reserve, which results in a high representation of the *ejidatarios* in the area despite the small sample size. We selected five

Table 1 Core variables used to identify ecological clusters (ecological variables), social-management clusters (social-management variables), and social-ecological system units (social-ecological variables)

Variable	Units	Description	Sources
Ecological variables- Individual plot scale (*ejidal* plot)			
Conserved forest[a]	%	Percentage of old forest cover (> 42 years old without disturbance) in landscapes at scale 650 m buffer (old forest area/total landscape area *100)	Mora et al. (2018), Pérez-Cárdenas et al. (2021)
Secondary forest[a]	%	Percentage of cover belonging to secondary forest (between 0 and 42 years of abandonment after disturbance) in landscapes at scale 650 m buffer (old forest area/total landscape area *100)	Mora et al. (2018), Pérez-Cárdenas et al. (2021)
Permanent crops[a]	%	Percentage of permanent crops cover in landscapes at scale 650 m buffer (old forest area/total landscape area *100)	Mora et al. (2018), Pérez-Cárdenas et al. (2021)
Introduced grasslands[a]	%	Percentage of introduced grasslands cover in landscapes at scale 650 m buffer (old forest area/total landscape area *100)	Mora et al. (2018), Pérez-Cárdenas et al. (2021)
Forest age[a]	Years	Number of years without being disturbed	Mora et al. (2018), Pérez-Cárdenas et al. (2021)
Carbon storage[a]	mgC ha^{-1}	Above ground biomass*0.48 (wood density for Chamela TDF, Martínez-Yrízar et al. 1992)	Mora et al. (2018)
Aspect degree[a]	Degree	Orientation of slope per point	Google Earth
Slope[a]	Degree	Gradient of the terrain per point	Google Earth
Elevation[a]	Metres	Elevation above sea level per point	Google Earth
Social-management variables—plot owner scale (*ejidatario*)			
Plot size[b]	Hectares	Total size of the land belonging to the *ejidatario* Cohen-Salgado (2014), Pérez-Cárdenas et al. (2021)	
No. years total use[c]	Count	Number of years the plot has been used	Cohen-Salgado (2014), Pérez-Cárdenas et al. (2021)
No. burnings per year[bc]	Count	Burnings carried out in the plot per year	Cohen-Salgado (2014), Pérez-Cárdenas et al. (2021)
No. cattle[d]	Count	Cattle average between the rainy season and the dry season owned by the ejidatario	Cohen-Salgado (2014), Pérez-Cárdenas et al. (2021)
No. paddocks[d]	Count	Paddocks within the plot	Cohen-Salgado (2014), Pérez-Cárdenas et al. (2021)
No. clearings per year[d]	Count	Clearings per year within the plot	Cohen-Salgado (2014), Pérez-Cárdenas et al. (2021)
Cattle rotation[d]	Categorical	Presence or absence	Cohen-Salgado (2014), Pérez-Cárdenas et al. (2021)
Forest clearing[d]	Categorical	Presence or absence	Cohen-Salgado (2014), Pérez-Cárdenas et al. (2021), Ramírez *unpublished data*

Table 1 (continued)

Variable	Units	Description	Sources
Intensity of wood extraction[bc]	Ordinal	0 = No extraction; 1 = less than 80 poles/ha; 2 = more than 80 poles/ha	Cohen-Salgado (2014), Pérez-Cárdenas et al. (2021), Mora et al. (2018), Ramírez *unpublished data*
Intensity of selective slashing[bc]	Ordinal	0 = No extraction; 1 = less than 200 rods; 2 = 200 or more rods/ha	Mora et al. (2018)
Intensity of cattle land use[bc]	Ordinal	0 = no cattle; 1 = less than 10 cows; 2 = more than 10 cows; 3 = more than 30 cows	Mora et al. (2018)
Intensity of forest use[bc]	Count	Sum of the indices Intensity of wood extraction, Intensity of selective slashing, and Intensity of cattle land use	Mora et al. (2018)
Social-Ecological variables- minimum governance units (*ejido*)			
Extension of *ejidal* plots[e]	Hectares	Average extension of the *ejidal* plots per *ejido*	RAN (2022)
Duration of private tenure (PROCEDE[f])[e]	Number of years	Number of years under the private scheme of PROCEDE	RAN (2022)
Area with individual *ejidal* land tenure[e]	%	Percentage of total area of the *ejido* linked to individual *ejidal* plots	RAN (2022)
Area with communal land use[e]	%	Percentage of total area of the *ejido* for communal use	RAN (2022)
Ejidatarios[e]	%	Percentage of landholding members of the *ejido* who are *ejidatarios* (they can vote and participate in the collective decisions for the *ejido* and can inherit the land)	RAN (2022)
Posesionarios[e]	%	Percentage of people owning land within the *ejido* but do not hold rights over communal lands and cannot vote in the assembly	RAN (2022)
Avecindados[e]	%	Percentage of landless people who have settled within the *ejido* for more than a year and do not possess land right nor vote in the Assembly but that can exercise individual agrarian capacity	RAN (2022)
No. federal Highways[e]	Count	Federal highways crossing the *ejido*	Calculated from RAN cartography
No. state highways	Count	State highways crossing the *ejido*	Calculated from RAN cartography

[a]Landscape original scale of data collection

[b]*Ejidal* plot original scale of data collection

[c]Ecological plot (50 × 50 m) original scale of data collection

[d]*Ejidatario* original scale of data collection

[e]*Ejido* original scale of data collection

[f]*PROCEDE* Program for Certification of *Ejido* Rights and Titling of Urban Plots

ordinal variables and five quantitative variables (see Table 1) for which consistent information was available across *ejidatarios*, and had shown to be key descriptors of tropical forest (dry and wet) management intensity: (1) land extension, (2) time of management, and (3) intensity of use (Benitez-Malvido 2006; Holl 2007; Martínez-Ramos and García Orth 2007; Zermeño-Hernández et al. 2015). We developed an index of management intensity in which the qualitative intensity (1 low, 2 intermediate, 3 high) was assessed for the nine most relevant variables that explained the variance among *ejidatario*.[1] Higher values in the index indicated greater management intensities. We summed the ordinal assessment to obtain a management intensity index per social-management cluster. The social data were linked with the ecological data based on their belonging to the same *ejido*, as there was not 100% correspondence between the *ejidal* plots and the *ejidatarios* (plot owners). We considered core variables for undertaking the analyses as those with less than 15% of missing data. The rest of the variables were used to complement the description of the clusters (more details in Table S.1). Nine variables with missing data (less than 15%) were imputed using the package "missMDA" (Josse and Husson 2016).

Minimum governance units: Data were gathered on the land tenure and on the communications infrastructure for nine *ejidos* (1400–18,000 ha); seven are in the transition area (Schroeder and Castillo 2013). Land rights held within the *ejidos* (Monroy-Sais et al. 2020) and distance to human settlements and roads (Maass et al. 2005; Flores-Casas and Ortega-Huerta 2019) have an important effect on the land cover transformation in the area. Therefore, data on the type of land tenure management (collective or individual), the types of land rights holders, and the number of years under private legal schemes (Program for Certification of *Ejido* Rights and Titling of Urban Plots, PROCEDE) were extracted from the National Agrarian Registry "Registro Agrario Nacional" (RAN 2022). The number of roads crossing the *ejidos* was obtained from the cartography provided by RAN (see Table 1).

[1] Number of cattle, number of years, plot size, wood extraction, selective slashing, number of paddocks, cattle rotation, number of clearings and number of pasture burnings.

Data analysis

The general clustering procedure consisted in performing a factorial analysis on each set of data (i.e. ecological, social-management, governance). Then we applied a hierarchical clustering on the components (HCPC) to identify clusters. Only principal components weighted with eigenvalues higher than 1 were included in the clustering procedure (i.e. Kaiser Criteria; e.g. Andrews et al. 2004). To identify the suitable number of clusters (e.g. similar plot types), we followed the entropy criterion that stops aggregating clusters when dissimilarity significantly decreased (Cornillon et al. 2012).

Ecological clusters (EC)

To find ecologically homogeneous *ejidal* plots, we first performed a principal component analysis (PCA) on the core ecological variables to summarise main patterns (Table 2). All the variables were previously transformed with log10 (n + 0.5) to avoid biases in the analysis. Once the clusters were created we used supplementary variables from soil data to further describe their characteristics (see Table 1). For points lacking soil information, data were estimated using Ordinary Kriging, which is considered a robust technique for spatial interpolation of soil properties (e.g. Robinson and Metternicht 2006).

Social-management clusters (SC)

To identify the social-management clusters, we performed a Factorial Analysis of Mixed Data (FAMD) using the core variables of the management carried out by the *ejidatarios* (Table 2; Lê et al. 2008). We described the clusters according to their management intensity.

Social-Ecological-Systems Units (SESU)

To identify Social-Ecological-Systems Units, we performed a PCA. We used the *ejido* as a unit of analysis and nine social-ecological variables that refer to access to land, land tenure, and governance (Table 2). Once the clusters were created, we used the percentage of plots from each *ejido* belonging to EC and the percentage of *ejidatarios* belonging to each SC as supplementary. We used these two variables to

Table 2 Variables used for the ecological, social-management, and social-ecological characterization

	Ecological	Social-management	Social-ecological
N[b]	63	67	9
Unit of analysis	*ejidal* plot (land parcel)	*ejidatarios* (plot owners)	*ejido* (smallest governance unit)
Quantitative variables	[9][a]	[6]	[9]
	% conserved forest % secondary forest	Plot size No. years total use	Mean *ejidal* plot extension (ha)
	% permanent crops	No. burnings per year	No. years in PROCEDE[c]
	% Introduced grasslands	No. cattle	% plots surface (ha)
	Forest age	No. paddocks	% land common use (ha)
	Carbon storage	No. clearings per year	% *ejidatarios*
	Aspect degree		% *avecindados*
	Slope		% *posesionarios*
	Elevation		No. federal highways
			No. state highways
Qualitative variables	[0]	[6]	[0]
	–	Cattle rotation	–
		Forest clearing	
		Intensity of wood extraction	
		Intensity of selective slashing	
		Intensity of cattle land use	
		Intensity of forest use	
Supplementary variables	[10]	[2]	[2]
	Soil available Phosphorus	*ejidatario*'s education level	% Ecological clusters per *ejido*
	Soil phosphatase activity	*ejidatario*'s age	% Social-management clusters per *ejido*
	Bulk density		
	Soil organic matter		
	% sand		
	% silt		
	% clay		
	pH		
	Water retention		
	Soil aggregates		
Data analysis procedure	PCA[d] → HCPC[e]	FAMD[f]→HCPC	PCA → HCPC

[a]Numbers between square brackets indicate the number of variables used per unit of analysis

[b]*N* The number of variables

[c]*PROCEDE* Program for Certification of *Ejido* Rights and Titling of Urban Plots

[d]*PCA* Principal Component Analysis

[e]*HCPC* Hierarchical Clustering on Principal Components

[f]*FAMD* Factor Analysis for Mixed Data

visualize how each SESU is associated with both EC and SC using a scatter plot.

We tested for significant differences among clusters at each scale (EC, SC, and SESU) by conducting ANOVA (for variables that are normally distributed) and Kruskal–Wallis tests to analyze differences in quantitative variables among clusters ($p < 0.05$). To test for the normal distribution of these variables, we used the Shapiro–Wilk test (Shapiro and Wilk 1965). Post hoc tests were implemented when significant differences among clusters were identified, using a Tukey and Dunn´s (with Bonferroni correction) test.

Table 3 Mean values and statistical differences for ecological variables in each Ecological cluster (EC)

	EC1	EC2	EC3	EC4	X^2
% Conserved forest	**72.03**[a]	55.09[ab]	37.64[b]	33.55[b]	23.57*
% Secondary forest[a]	5.09[a]	11.69[a]	**23.20**[b]	12.90[ab]	23.53*
% Permanent crops	**7.99**[a]	0.82[b]	0.50[b]	0.08[b]	14.74*
% Introduced Grasslands[a]	10.15[a]	31.72[b]	32.62[b]	**47. 91**[b]	22.64*
Forest age	**52.02**[a]	42.38[a]	34.66[a]	2.75[b]	25.38*
Carbon storage[a]	19.98[bc]	15.88[b]	**27.85**[c]	2.50[a]	28.13*
Aspect	1.58[a]	0.76[a]	**22.25**[b]	12.67[b]	45.60*
Slope	4.48[a]	**11.49**[b]	11.37[b]	7.09[ab]	20.83*
Elevation[a]	58.47[a]	**179.09**[b]	122.32[b]	162.00[b]	24.53*
Phosphatase activity	767.59[ab]	730.26[ab]	**827.93**[b]	671.14[a]	10.93*
Bulk density	1.36[ab]	1.38[ab]	1.31[a]	**1.42**[b]	8.27*

Bold values represent the classes with the highest mean values for each of the variables. Different letters indicate significant differences according to Dunn's multiple comparison test with Bonferroni correction ($p < 0.05$)

[a]Variables that contributed the most to the three principal components that had high eigenvalues (> 1)

*Significance level at 5%

To evaluate differences among clusters for qualitative data, we used the chi-square test.

All the analyses were carried out using the FactoMineR package (Lê et al. 2008) for R version 4.0.5 (R core Team 2014). We used the packages "car" (Fox and Weisberg 2019) for the ANOVAs, the package "multcomp" (Hothorn et al. 2008) for the post hoc tests, and "FSA" (Ogle et al. 2023) for the Dunn test.

Results

Ecological clusters (EC)

Ejidal plots mainly differed with respect to their land cover, carbon storage and topography (elevation, slope, aspect) (Fig.S.1). The three first principal components explained 69.5% of the variance (Table S.2). The first dimension PCA1 (34%) divided the plots along a gradient ranging from those covered by old growth forest to those with introduced grasslands. PCA2 (20%) showed a strong association between carbon storage, elevation, and slope. PCA3 (15%) grouped plots at higher altitudes covered with secondary forests (Table S.3).

The four clusters represented a gradient of land-use intensity that is embedded into the heterogeneous landscape of the Chamela-Cuixmala region (Tables 3, S.4; Fig. S.2). The first cluster, EC1 comprised *Ejidal* plots that had significantly more conserved forests (72%) of older ages (~52 years old), as well as those with the highest percentage of permanent crop cover, which are located adjacent to the Biosphere Reserve (Fig. 3). The second cluster, EC2 included the *Ejidal* plots found at the highest elevations (> 160 m) and in sites with steepest slopes (> 11.40°), mostly including older aged forests (~42 years old), and were mostly found northeast of the Biosphere Reserve (Fig. 3). The third cluster, EC3, comprised *Ejidal* plots with the highest values of carbon storage (27.85 mgC ha^{-1}), and soils with the highest levels of phosphatase activity (827), were mostly found in moderate north-facing slopes with high coverage of secondary forests (23%), and north of the Biosphere Reserve. The fourth cluster, EC4, was dominated by *Ejidal* plots covered by introduced grasslands (47%) with the most compacted soils (with a high bulk density 1.42), northeast-oriented, and found across the Chamela-Cuixmala region (Fig. 3).

Social-Management Clusters (SC)

Ejidatarios mainly differed in the way they manage their land with respect to the number of cattle owned, the number of years using their plot, the intensity of wood extraction and plot size (Fig.S.3). The first seven components of the FAMD explained 77% of the variance (Table S.5). The first dimension FAMD1

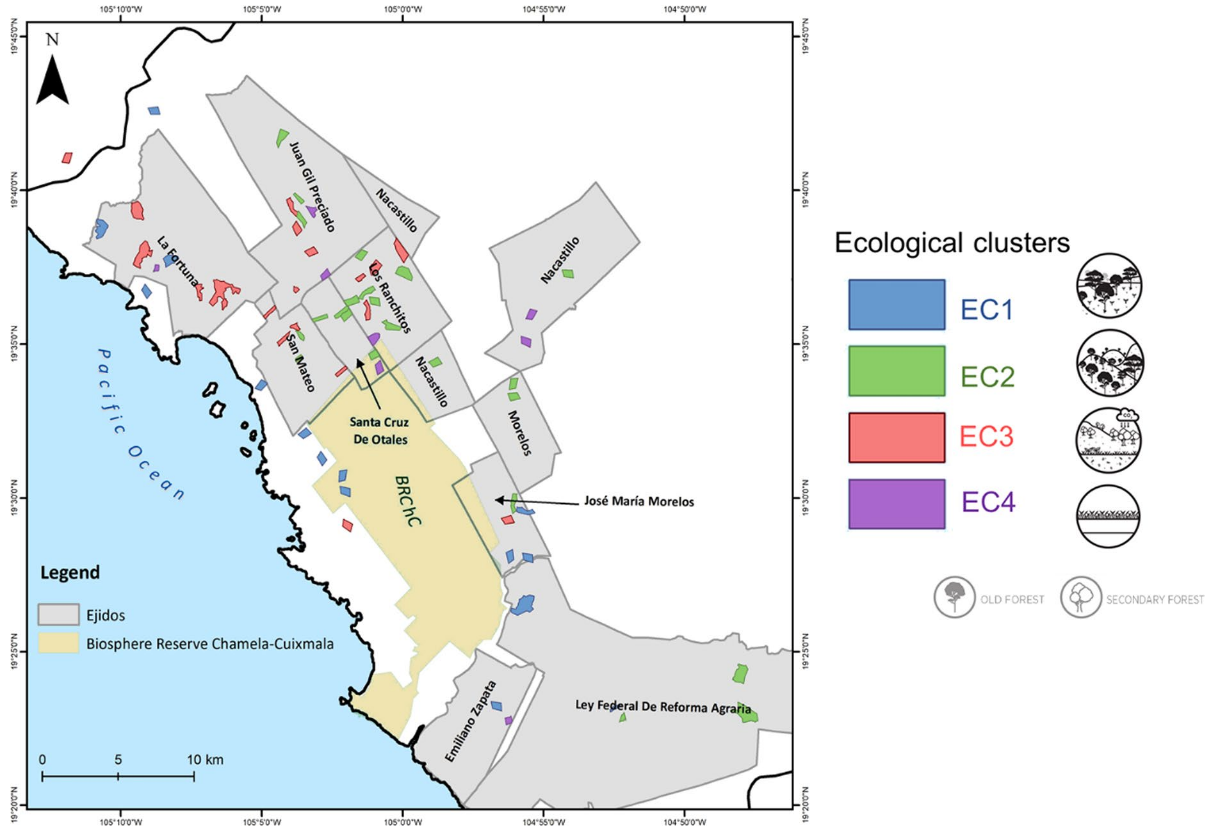

Fig. 3 Geographical representation and description of the ecological clusters (EC) at the *ejidal* plot level. EC1 = Dominance of conserved and old forests. Permanent crops. EC2 = Highest elevations and slope. Dominance of old forests. EC3 = Dominance of secondary forests. High carbon storage. High phosphatase activity in soil. Moderate slopes facing north. EC4 = Dominance of introduced grasslands. Compacted soil (high bulk density). Northeast oriented

(21%) divided the owners based on the number of cattle owned. FAMD2 (15%) was associated with the number of years of using the plots. FAMD3 (11%) was related to the intensity of wood extraction and plot size. FAMD4 (8%) represented the intensity of selective slashing. FAMD5 (7%) represented the differences regarding the number of paddocks. FAMD6 (7%) was associated with cattle rotation. FAMD7 (6%) was related to the number of clearings per year (Table S.6).

Four social-management clusters (SC) of the plot owners revealed a gradient in management intensity (Figs. 4, S.4). SC1 managed their plots for a longer time (35 years on average), had no forest clearings and no or low wood extraction, lowest cattle owned (10–32), and 93% of them rotated the cattle among paddocks. SC2 had the largest plot sizes (~136.4 ha) and numbers of cattle owned (~82 cows). SC3 performed the most intense pasture management, with the highest frequency of burning (5 times) and clearing (9), and owned the smallest plots (44 ha). SC4 undertook the highest intensity of wood extraction and slashing (>200 rods/ha, and 80 poles/ha respectively); 100% of them do clearings, and 75% do not rotate their cattle. While the nature of the management is heterogeneous within and among SC, the intensity index revealed a gradient from SC1 with the lowest overall management intensity, to SC2, SC3 and SC4, with the highest overall management intensity (Tables S.7, S.8).

We observed an association between plot size and management intensity; larger plots tended to have the lowest management intensity (SC1), while plots with the most intensive management were smaller (SC3 and SC4) (Table 4). A gradient was also observed in cattle rotation since larger plots represented by SC1

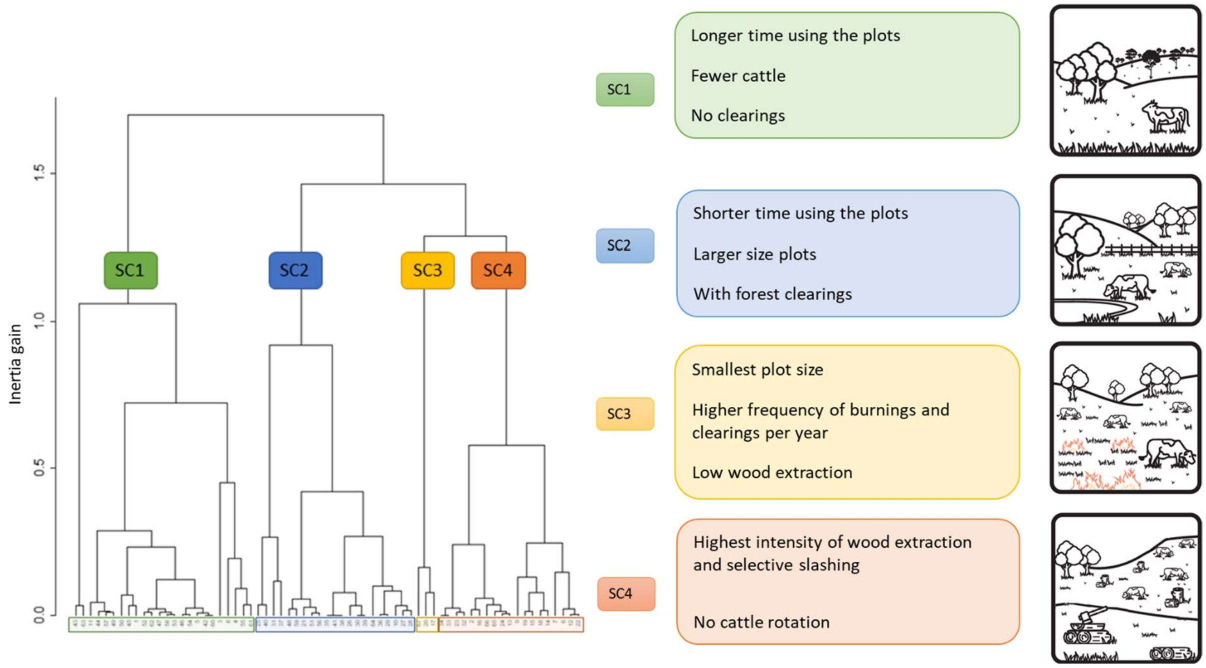

Fig. 4 Dendrogram of the social-management clusters (SC) at the *ejidatarios* level and their description

were the ones where 100% of the *ejidatarios* rotated cattle, while smaller plots are related to less cattle rotation (SC3) (Table 4). In addition, those plots represented by SC4, where there is the least cattle rotation, are the ones with the highest intensity of wood extraction (Table 4).

Social-ecological systems units (SESU)

The variance among *ejidos* was mainly explained by the percentage of total *ejidal* surface allocated to individuals, the number of years under private tenure (registration in PROCEDE), and the average individual *ejidal* plot extension (Fig. S.5). The first three components of the PCA presented eigenvalues greater than 1 and explained 87% of the variance (Table S.9). PCA1 (41% of the variance) divided the *ejidos* based on the percentage of ejidal surface allocated to common lands versus those allocated to individuals. There was a positive relation between the number of *ejidatarios* per *ejido* and the percentage of common lands, and between the number of *avecindados* and the percentage of land allocated to individuals. PCA2 (26%) showed a strong relation with the number of years under the private tenure of PROCEDE. PCA3 (20%) grouped *ejidos* according to the average size of the individual plots (Table S.10).

The four social-ecological systems units (SESU) differed with respect to communal or individual governance and tenure rights. SESU1 and SESU4 were the most dissimilar, representing a gradient characterised by the percentage of land allocated to individuals, the percentage of *avecindados*, and the percentage of *ejidatarios* (Figs. 5, S.6; Table 5). The duration under private tenure regulated by PROCEDE explained the differences between SESU2 and SESU3 (Tables 5, S.11).

SESU1 comprised the *ejidos* Nacastillo and José María Morelos in the eastern part of the Biosphere reserve (Fig. 5). These *ejidos* do not have land allocated to individuals and had the highest percentage of *ejidatarios* (97%). SESU2 included the *ejidos* Los Ranchitos and Juan Gil Preciado at the North of the Biosphere Reserve, and had the higher number of years under the private schemes of PROCEDE (26 years) and the highest average size of individual (*ejidal*) plots (27 ha). SESU3 comprised two *ejidos* at the north and south of the Biosphere, i.e. Santa Cruz de Otates and Ley General de Reforma Agraria. The *ejidos* of SESU3 were the last ones to join the private

Table 4 Mean values and statistical differences for social-management variables in each Social cluster (SC)

Social variables quantitative	SC1	SC2	SC3	SC4	X^2	F-value
Plot size	87.19^{a}	**136.47**^{b}	44.15^{a}	64.25^{ab}		7.30*
No. years total use	**35.28**^{b}	8.91^{a}	31.12^{b}	30.50^{ab}	29.40*	
No. burnings per year	0.10^{a}	3.01^{b}	**5.03**^{b}	4.25^{b}	47.24*	
No. cattle	32.85^{a}	**82.35**^{b}	54.28^{ab}	52.83^{ab}	16.61*	
No. paddocks	1.70^{a}	2.45^{b}	2.11^{ab}	**2.75**^{ab}	13.20*	
No. clearings	3.67^{a}	4.35^{ab}	**9.41**^{b}	4.13^{ab}	13*	
Intensity of forest use	2.24^{a}	2.00^{a}	3.41^{b}	**6.25**^{b}	25.5*	

Social variables Qualitative	SC1	SC2	SC3	SC4	X^2
Cattle rotation*					
No	6.9	0	35.3	**75**	19.24*
Yes	93.1	**100**	64.7	*25*	
Forest clearing*					
No	**69**	6.3	0	0	33.06*
Yes	31	93.7	**100**	**100**	
Intensity of wood extraction*					
0 = No extraction	**82.8**	56.3	5.9	0	81.3*
1 < 80 poles/ha	13.8	43.8	94.1	0	
2 > 80 poles/ha	3.4	0	0	**100**	
Intensity of selective slashing					
0 = No extraction	86.1	87.5	**94.1**	0	35*
1 < 200 rods	13.8	0	5.9	25	
2 ≥ 200 rods/ha	0	12.5	0	75	
Intensity of cattle land use					
0 = no cattle	6.9	18.8	0	0	21
1 < 10 cows	13.8	43.8	6	0	
2 > 10 cows	62.1	25	47	50	
3 > 30 cows	17.2	12.5	47	**50**	
Ejidatario's education level					
Elementary	3.4	**43.8**	17.6	25	23
High school	6.9	0	5.9	0	
None	20.7	**31.3**	0	0	
Secondary	65.5	18.8	**76.5**	75	
University	3.4	**6.3**	0	0	

Management intensity index	SC1	SC2	SC3	SC4
Number of cattle	1	3	2	2
Number of years of use	3	1	3	3
Plot size	2	3	1	2
Wood extraction	1	1	2	3
Selective slashing	1	1	1	3
Number of paddocks	1	2	2	3
Cattle rotation	1	1	2	3
Clearings	1	3	3	3

Table 4 (continued)

Management intensity index	SC1	SC2	SC3	SC4
Pasture burning	1	2	3	3
Total (index of management intensity)	12	17	19	25

Bold values represent the classes with the highest mean values for each of the variables. Different letters indicate significant differences according to Dunn's multiple comparison test with Bonferroni correction ($p < 0.05$)

*Significance level at 5%

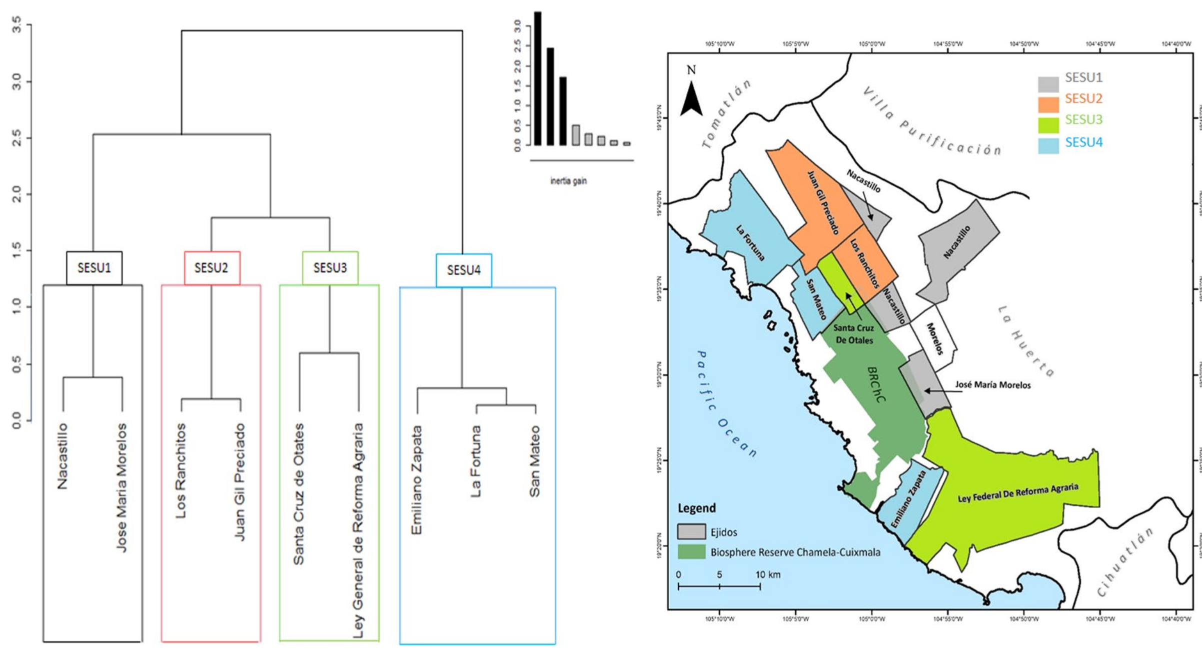

Fig. 5 Left: Dendrogram of the Social-Ecological Systems Units (SESUs) at the *Ejidataro* level. Right: SESUs shown in the map of *Ejidos* surrounding the Chamela-Cuixmala Biosphere Reserve

scheme of PROCEDE (18 years under PROCEDE). SESU4 included the *ejidos* Emiliano Zapata, La Fortuna, and San Mateo, which are at the north and south of the Reserve, closest to the coastline and with the highest percentage of *avecindados* (72%), and the lowest percentage of *ejidatarios* (24%). Finally, SESU3 and SESU4 presented the highest percentage of surface allocated to individuals (79%).

While topography (EC) and plot owner individual resources (SC) underpin land cover transformations and management intensity, they are also modulated by communal governance (Fig. 6, SESU). SESU4, the most distinct one (Fig. 6), was ecologically characterised by flatter lands at lower elevations (less EC2) and secondary forests with high phosphatase (as represented by EC3) (Tables 3, 5). At the same time, SESU4 was dominated by *ejidatarios* who frequently undertake burnings and clearings (SC3) (Table 4). It presented a highest percentage of *avecindados*. By contrast, SESU1 was characterised by the high % of *ejidatarios*, and dominated by mature forests, including the oldest groves (EC1), and those at the highest elevations (EC2); socially it was dominated by *ejidatarios* with the largest plot size (SC2), moderate cattle management intensity with no rotation and the highest wood extraction most frequent forest management (SC4) (Table 4). In between SESU1 and SESU4, SESU2 and SESU3 presented an intermediate land-cover transformation (Fig. 6), but differed with respect to the number of years under private tenure of PROCEDE (Table 5). In addition to the longest period under PROCEDE, SESU2 is also

Table 5 Comparison of mean values for governance variables at the *ejido* level per each Social-Ecological System Unit (SESU)

	SESU1	SESU2	SESU3	SESU4	F-value	X^2
Ejidal plots extension (ha)	9.10^{b}	**27.35^{a}**	17.75^{ab}	13.83^{ab}	6.77*	
No. years in PROCEDE	23^{ab}	**26^{a}**	18^{b}	24^{a}	11.81*	
% Surface allocated to individuals	0^{b}	77^{ab}	**79.31^{a}**	**78.34^{a}**	7.28*	
% *Ejidatarios*	**97.02^{a}**	80.32^{ab}	88.65^{ab}	24.31^{bc}		0.0167
% *Avecindados*	0^{a}	14.44^{ab}	9.45^{ab}	**72.61^{b}**		0.0167

% Ecological and social-management clusters per SESU	SESU1	SESU2	SESU3	SESU4	X^2
EC1	**33**	0	20	29	19.15*
EC2	**33**	**45**	**70**	11	
EC3	11	**40**	0	**47**	
EC4	**22**	15	10	11	
SC1	11	**75**	0	20	42.4*
SC2	**56**	6	**67**	20	
SC3	11	15	33	**53**	
SC4	**22**	4	0	7	
Ejidos	Nacastillo José M. Morelos	Ranchitos Juan Gil Preciado	Santa Cruz de Otates LGRA	Emiliano Zapata La Fortuna San Mateo	

Bold values represent the classes with the highest mean values for each of the variables. Different letters indicate significant differences according to Dunn's multiple comparison test with Bonferroni correction ($p < 0.05$)

*Significance level at 5%

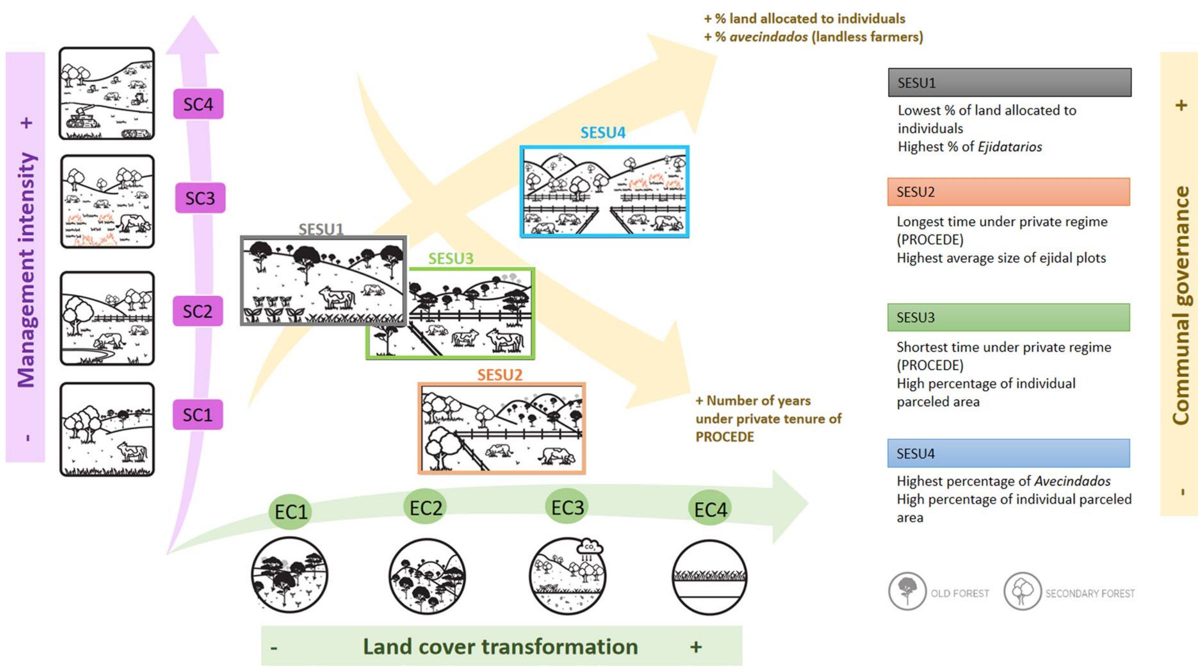

Fig. 6 SESU association regarding the highest percentage of Ecological clusters (EC) and Social-management clusters (SC). Right boxes represent the SESU description regarding social-ecological variables

characterized by a majority of *ejidatarios* with the lowest management intensity (SC1). SESU3 instead, had the lowest number of years under private tenure of PROCEDE and was dominated by plots at the highest elevations (EC2), where *ejidatarios* had the largest plot size (SC2) (Tables 3, 4).

Discussion

Land-use intensity and trade-offs between nature's contributions to people: the relevance of co-production

Topography was a major driver of land use change within individual *ejidal* plots. Areas with rugged topography tended to maintain more forest cover while flatter areas have been more drastically transformed into pastures. This supports other studies focused on the role of topography in land cover change (Martín-López et al. 2017; Flores-Casas and Ortega-Huerta 2019; Aik et al. 2021). The prevalence of secondary forest in some of the plots results in a combination of productive activities that suggested that biodiversity conservation and livelihoods can be reconciled under certain conditions, similar to as found elsewhere (Pérez-Cárdenas et al. 2021; Balvanera et al. 2021). From our results, we found that important nature contributions to people, such as regulation of soil quality (represented by high phosphatase activity[2] and less soil compaction) and regulation of climate change (measured with the variable carbon storage) are provided in these forests (EC3; Table 3). By contrast, in the introduced grasslands (EC4; Table 3), phosphatase is usually low and soil compaction is high, indicating the low provision of soil quality. It is also in the introduced grasslands where the most widespread land use is intensive cattle farming (SC4; Table 4), which suggested a relation between intensive rangeland use and soil degradation, something previously reported at the plot scale (Jaramillo et al. 2003; Trilleras et al. 2015; Ayala-Orozco et al. 2018).

The size of the plots owned by *ejidatarios* underpins their decisions about management. For example, most *ejidatarios* do not use their entire plot for cattle due to factors like the high cost to transform forests into grasslands in areas with high slopes (such as SESU 1 and SESU 2, Fig. 6). Conversely, *ejidatarios* of small-sized plots use the greatest amount of available resources, removing the forest area and intensifying the management of the land (SC3 and SC4; Table 4).

Decisions on how to manage land in the Chamela-Cuixmala Region are based on adaptive management and learning processes, as well as access to anthropogenic capitals (Sánchez-Romero et al. 2021). *Ejidatarios'* motivations to burn or not to burn their land depend on their benefit–cost knowledge (i.e. human capital) (Ramírez-Ramírez et al. *in review*), which supports that nature's contributions also require inputs from humans, a process known as "co-production" (Díaz et al. 2015; Palomo et al. 2016). Recent empirical research has shown that the type of anthropogenic capital involved in the co-production determines the level of land-use intensity and leads to trade-offs and synergies among nature's contributions (Torralba et al. 2018; Lavorel et al. 2020; Bruley et al. 2021). García-Llorente et al. (2015) found that while high use of inorganic pesticides, fertilizers, and technology (manufactured and financial capitals) was strongly used in intensively managed greenhouses in the lowlands of Sierra Nevada Mountains, small-scale farming systems at higher altitudes were mainly supported by collective action of irrigation communities (i.e. social capital). Studies on how spatial configuration of the use of anthropogenic capitals lead to trade-offs between nature's contributions to people and maintenance of multi-functional landscapes contribute to reconciling biodiversity conservation and productivity activities (e.g. Schermer et al. 2016; Pachoud et al. 2020; Grosinger et al. 2021).

The examples portrayed above highlight the relevance of operationalizing social-ecological system units (SESU), only possible if there is long-term interdisciplinary research, and collaborative efforts to create place-based social and ecological datasets (Haberl et al. 2006; Collins et al. 2010; Maass et al. 2016). In this study, the characterization of a large number of plots (N = 67) based on a wide range

[2] Phosphatase activity is a good indicator of soil quality in TDF because phosphorus is the element most limiting plant productivity (Campo et al. 2001) and is affected by land management in the long term (Van Der Sande et al. 2022). This enzyme helps to release phosphorus it from the organic forms of decomposing biomass thus improving local P recycling and P availability in the absence of other sources, such as P fertilizers, that are not used in this region (Sandoval-Pérez et al. 2009).

of ecological variables (N = 20) was only possible because of the collaborative nature of the long-term explorations of the social-ecological dynamics in the Chamela-Cuixmala region (Maass et al. 2005, 2016; Balvanera et al. 2021). Likewise, the identification of social-management clusters relied on a rich database of in-depth interviews to *ejidatarios* (N = 63) conducted over time.

Although there have been some efforts to collect social and ecological data in long-term research programs (e.g. Fischer et al. 2010; Bretagnolle et al. 2019), challenges remain around mismatches between ecological, social, and management data. Although our methodological approach was limited by our sample size that might not have fully represented existing ecological conditions within *ejidal* plots (Cohen-Salgado 2014), the spatial representation of *ejidal* plots and *ejidos* was critical to explore social-ecological dynamics for the Chamela-Cuixmala region.

Land management decisions: the relevance of governance systems across scales

Decisions of plot owners (*ejidatarios*) were bounded by the topographical characteristics of their plot, and by the governance system in which their decision-making is embedded. Historical privatization trends and level of communal management (see the introduction and Supplementary information 1) have had a clear impact on the social-ecological dynamics in the Chamela-Cuixmala region. For example, the *ejidos* that were the last in applying the private tenure fostered by PROCEDE (i.e. Santa Cruz de Otates and Ley General de Reforma Agraria—SESU3) are the *ejidos* with the highest percentage of surface allocated to individuals, with a high number of *ejidatarios* and large plot sizes (Table 5). This governance of land tenure has led to a moderate management intensity that allows the co-existence of forest preservation and productive activities. Including the governance level in our approach made visible similarities between *ejidos* that are very distinct in ecological and social-management conditions (i.e. SESU3). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) explicitly recognized this central role of governance in its conceptual framework and stated that governance systems determine, to various degrees, the access to, and the control, allocation, and distribution of components of nature and anthropogenic assets and their benefits to people" (Díaz et al. 2015, p. 6).

There are social-ecological dynamics mediated by land management decisions that were not covered in this study and should be considered in future research. For example, (Vallet et al. 2019) found that the co-production of nature's contributions to people were subject to inequalities in access to different types of capital. In addition, Martín-López et al. (2019) found that power relations were exerted across governance scales, where institutions and stakeholders at larger scales often shape the decisions of local actors. Therefore, future social-ecological research in the Chamela-Cuixmala region needs to explore the role played by external stakeholders, such as external land buyers who recently arrived in the region, or landless inhabitants that can rent or work the land, power dynamics that shape the distribution of access to land, and the anthropogenic capitals underpinning co-production (Felipe-Lucia et al. 2015; Berbés-Blázquez et al. 2017; Vallet et al. 2019; Martín-López et al. 2019).

Moreover, this study did not evaluate the optimum number of clusters produced by different clustering statistical methods, and did not validate the SESU characterizations with the *ejidatarios* and other relevant stakeholders of the Chamela-Cuixmala region. Future applications of this methodology should consider a broad spectrum of available biophysical, social, and governance data, test for different clustering methods, and validate the results with relevant stakeholders. Here, it is important to point out that the resulting SESU maps are statistical constructs and might differ from the maps constructed by different stakeholders. Yet, the SESU maps obtained through the suggested methodological approach can create spaces for dialogues with different stakeholders about sustainable management options.

Conclusions

Place-based research on social-ecological systems has immensely advanced in the last decade by deepening the understanding of human-nature interactions across scales (Epstein et al. 2015; Folke et al. 2021; Norström et al. 2022). This body of research demonstrates that although social-ecological interactions are of relevance at larger scales than locally, it is usually at the local scale where diverse and innovative solutions emerged to reconcile productive activities and biodiversity conservation (Norström et al. 2022). This study provided a multi-scale methodological approach to identify spatially explicit social-ecological units across three decision-making scales. This approach helped address scale mismatches between ecological, social, and governance data, and navigate the inherent complexities of the interactions between people and nature.

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Author contributions PS-C: Conceptualization, Formal analysis, Investigation, Writing—original draft, Visualisation. PB: Conceptualization, Writing—original draft, funding acquisition, Supervision. ST: Spatial analysis, maps creation, Writing—review & editing. FM: Data ownership (collection), Writing—review & editing. NP-C: Data ownership (collection), Writing—review & editing. DC-S: Data ownership (collection), Writing—review & editing. RR-R: Data ownership (collection), Writing—review & editing. MEG: Data ownership (collection), Writing—review & editing. BM-L: Conceptualization, Writing—review & editing, funding acquisition, Supervision.

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Declarations

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

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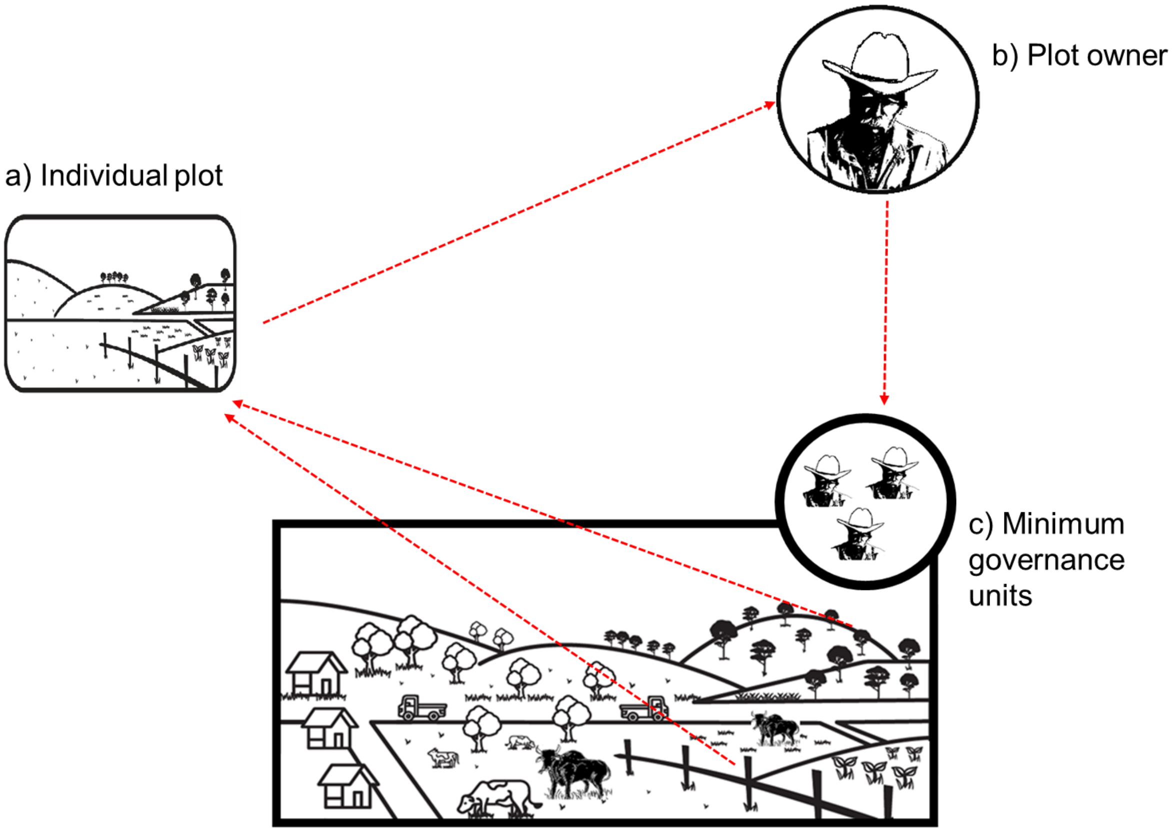
Supplementary Information

Supplementary information 1 *Ejidos* historical context and management decisions

A dramatic change in the functioning of *ejidos* occurred in 1992 when a change to the Mexican constitution was approved to convert semi-communal lands into private property (DOF, 1992). The federal government launched the program PROCEDE (Program for Certification of *Ejido* Rights and Titling of Urban Plots) through which individual *ejidatarios* can now fully own their parcels, common lands, and urban plots. PROCEDE provided individual land parcels as well as communal ones with the right titles over such land (Galicia-Castillo, 2009). This new law also allowed fulling privatizing of an *ejido* including the common lands (Schroeder and Castillo 2013). Privatization of *ejido* fragmented smallholder communities, weakening *ejido* institutions and local governance (Schroeder and Castillo 2013, Lazos-Chavero et al. 2016). However, depending on the *ejido* and its self-organization the impact of that reform has had a greater or lower impact on forest management decisions and collective action management (Schroeder and Castillo 2013, Monroy-Sais et al. 2020).

Supplementary information 2 Decision-making scales in the Chamela-Cuixmala region



Decision-making scales/units of analysis relevant to the Tropical Dry Forest (TDF) management in the Chamela-Cuixmala region. A) *Ejido*: semi-communal land tenure with private and communal lands ranging from 1400 to 18000 hectares; B) *Ejidatario*: plot owner with legal rights to inherit and sell the land, as well as to vote in the Assembly for making decisions on the communal areas, may own several *Ejidal plots distributed in several areas of the Ejido.*; C) *Ejidal* plot: individual plots owned by the *ejidatarios* where the decisions take place (ranging from 7 to 30 hectares)

Supplementary information 3 Soil collection methods description

Three soil samples were taken in each site on three positions along a transect, each 5 m apart, with a soil borer down to 15 cm depth. The sample included only mineral soil and additionally another soil sample was taken to the same depth with a PVC cylinder of known volume, adjacent to the first sampling positions. The first sample three soil samples were pooled and used for chemical and physical analyses performed on the soil fraction ≤ 2 mm, after sieving. Particle size distribution indicating the quality of the soil mineral base was measured with after pretreatment overnight in 0.5% sodium hexametaphosphate (Kroetsch, 2006). Soil organic matter content informing the accumulation of soil carbon was measured after wet acid digestion (Walkley and Black, 1934). Bulk density, an indicator of soil compaction that diminishes root growth, water storage and infiltration, and increases erosion due to run-off, was measured from the three samples of known volume after oven-drying at 105 °C for 2-5 days and dividing the oven-dry mass by the fresh volume. Soil content of sand-free water-stable aggregates, a measure of soil structure providing aireation, water infiltration and retention, and microbial activity, was measured by wet sieving (Hallet et al. 2009) to obtain fractions >0.250 mm (0.250-1, 1-4, >4), dissolving to remove sand particles, second sieving and drying. The mass of three fractions was added. Soil water retention capacity, an indicator of the soil capacity to retain rainfall water, was measured after packing a soil column to a density of 1 g cm^{-3} watering to saturation and allowing free drainage overnight. The soil water content after drainage was calculated weighing a sample extracted from the column in fresh and after drying completely. Refrigerated and finely ground soil samples were used for the following measurements. We measured pH in water using a 1:5 soil:water ratio and a pH meter, as a measure of chemical conditions for nutrient availability. Available soil phosphorus, the most limiting nutrient in this ecosystem, was determined using a wide pH-spectrum Mehlich 3 extractant solution (Mehlich, 1984), and orthophosphate concentrations were quantified colorimetrically using molybdate colorimetric determination with Auto Analyzer III method. Phosphatase enzymatic activity is a measure of biological activity capable of converting insoluble phosphorus forms in soluble forms that can be taken up by most organisms. Soil acid/alcaline (depending on soil pH) phosphatase activity was determined colorimetrically as in Tabatabai and Bremner (1969).

Table S.1 Supplementary variables used for cluster description

	Variable	Description	Original scale of data collection	Source
Ecological variables- *Ejidal* plot scale				
	Soil available phosphorus (mg kg^{-1})	Most limiting nutrient for plant growth	Ecological plot (50x50 m), *Ejidal* plot	Gavito et al. unpublished data
	Soil phosphatase activity (µg para-nitrophenol g^{-1} soil h^{-1})	Enzyme involved in cycling of organic phosphorus	Ecological plot (50x50 m), *Ejidal* plot	Gavito et al. unpublished data
	Soil bulk density (g cm^{3})	Measure of soil porosity and compaction	Ecological plot (50x50 m), *Ejidal* plot	Gavito et al. unpublished data
	Soil organic matter (%)	Concentration of organic material conferring fertility	Ecological plot (50x50 m), *Ejidal* plot	Gavito et al. unpublished data
	% sand	Soil mineral base not conferring fertility	Ecological plot (50x50 m), *Ejidal* plot	Gavito et al. unpublished data
	% silt	Soil mineral base conferring low fertility	Ecological plot (50x50 m), *Ejidal* plot	Gavito et al. unpublished data

	% clay	Soil mineral base conferring high fertility	Ecological plot (50x50 m), *Ejidal* plot	Gavito et al. unpublished data
	Soil pH	Chemical conditions for nutrient availability	Ecological plot (50x50 m), *Ejidal* plot	Gavito et al. unpublished data
	Soil water retention capacity (%)	Maximum water storage capacity	Ecological plot (50x50 m), *Ejidal* plot	Gavito et al. unpublished data
	Soil aggregates (g g^{-1} dry soil)	Soil structure conferring aeration, water retention and microbial activity	Ecological plot (50x50 m), *Ejidal* plot	Gavito et al. unpublished data
Social-management variables- *Ejidatario* scale				
	Ejidatario´s education level	0=None, 1=elementary, 2=secondary, 3=high school, 4= University	*Ejidatario*	Cohen 2012, Perez-Cárdenas et al. 2021, Ramírez et al. in prep.
	Ejidatario´s age	Number of ejidatario´s age in years	*Ejidatario*	Cohen 2012, Perez-Cárdenas et al. 2021, Ramírez et al. in prep.
Social-ecological variables- *Ejido* scale				
	Ecological clusters (%)	Percentage of plots from each *ejido* belonging to each EC	*Ejidal* plot	This study
	Social-management clusters (%)	Percentage of *ejidatarios* from each *ejido* belonging to each SC	*Ejidatario*	This study

Figure S.1 Correlation circle from the principal component analysis (PCA) on the Ecological variables. Blue variables represent the supplementary variables

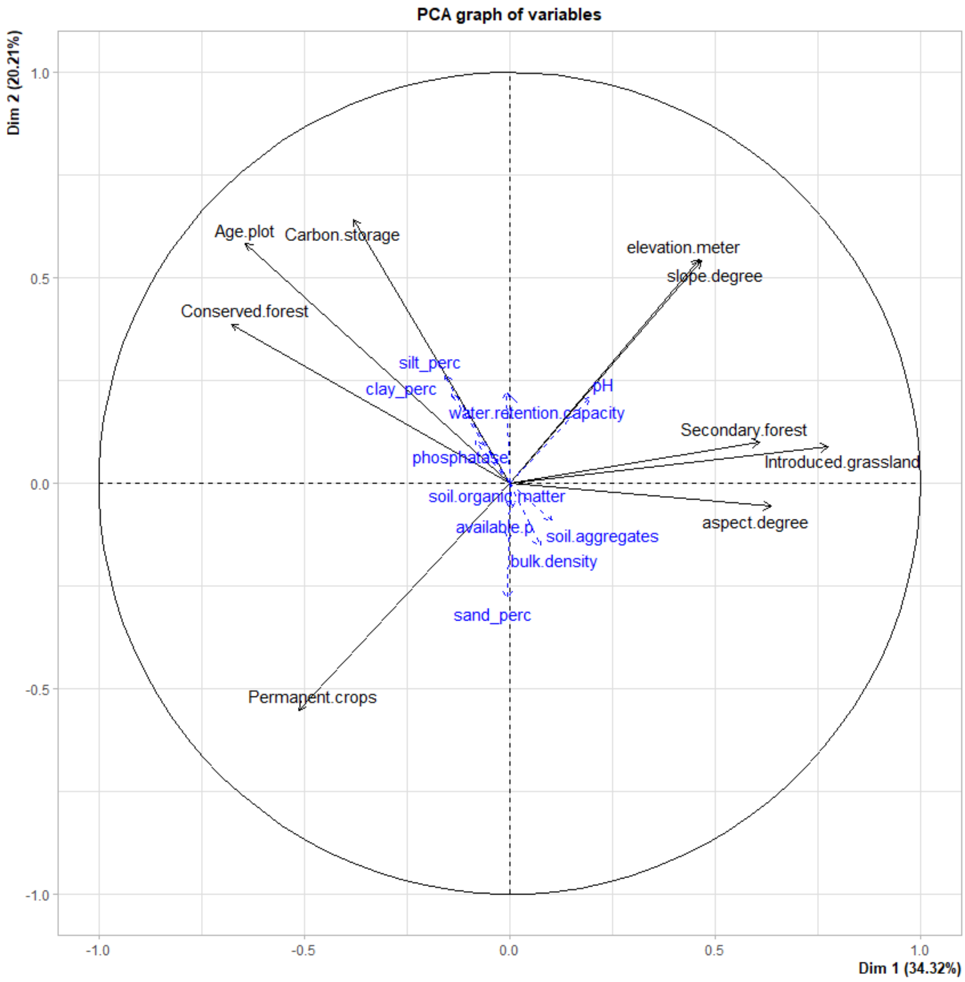


Table S.2 Variance explained per principal component from the PCA on the Ecological variables

	eigenvalue	percentage of variance	cumulative percentage of variance
comp1	3.0883744	34.315271	34.31527
comp2	1.8191728	20.213032	54.5283
comp3	1.3471809	14.968676	69.49698
comp4	0.7724797	8.583108	78.08009
comp5	0.7464674	8.294082	86.37417
comp6	0.5294584	5.882871	92.25704
comp7	0.2924231	3.249146	95.50619
comp8	0.2493488	2.770543	98.27673
comp9	0.1550944	1.723271	100

Table S.3 Ecological variables contribution per dimension (eigenvalue > 1) on the PCA. Bold numbers and variables indicate the highest values and variables contribution per dimension.

Variables contribution per dimension			
	Dim.1	Dim.2	Dim.3
Conserved.forest	14.866	8.223	2.567
Secondary.forest	12.019	0.546	22.565
Permanent.crops	8.506	16.714	11.028
Introduced.grasslands	**19.512**	0.435	0.025
Carbon.storage	4.641	**22.686**	19.011
Forest age	13.375	18.762	4.525
slope	7.052	16.127	2.265
elevation	6.896	16.333	**23.710**
aspect	13.134	0.175	14.303

Figure S.2 Individuals map (*ejidal* plots) from the ecological clusters (EC)

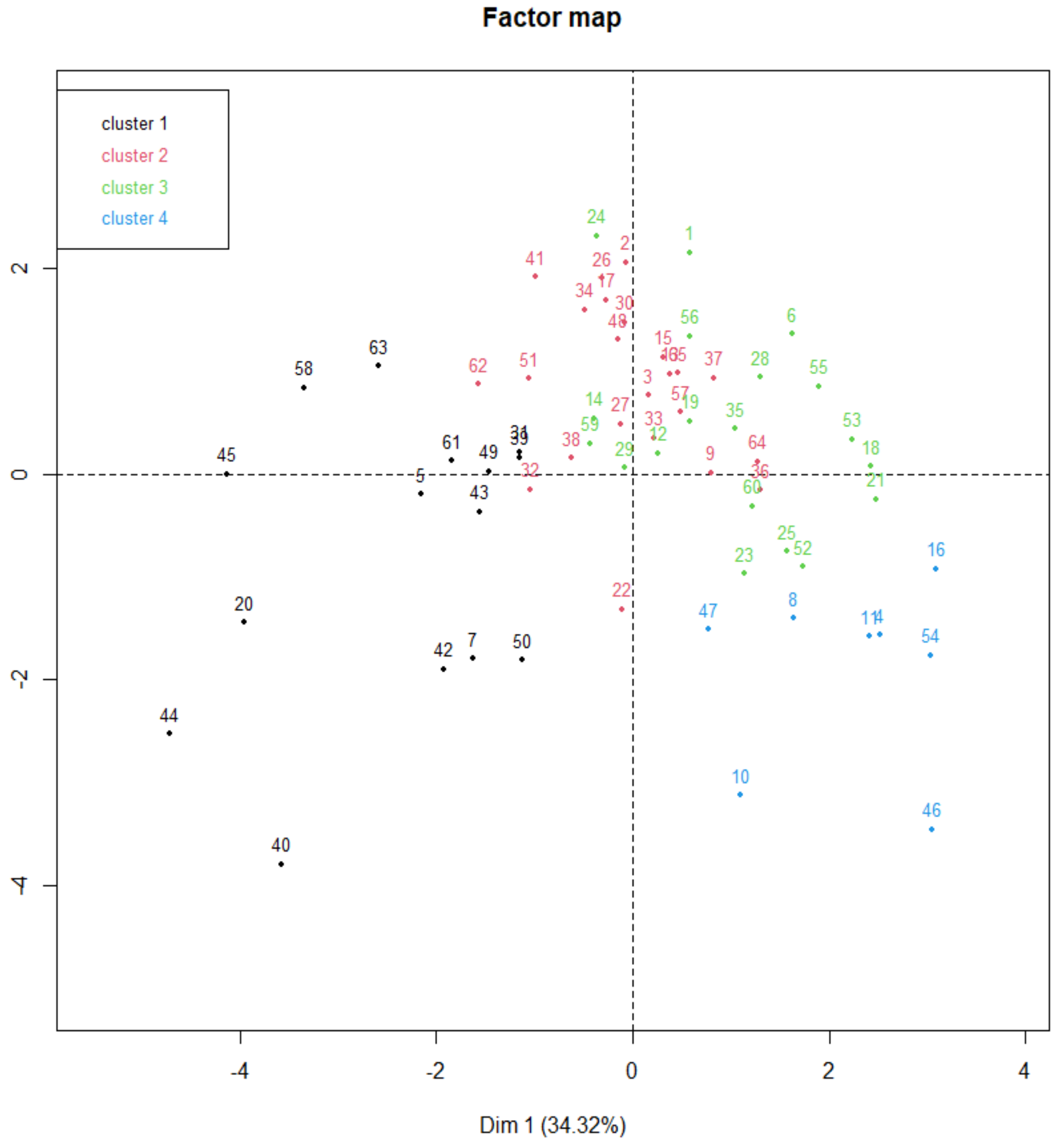


Table S.4 Description of each ecological cluster (EC) by quantitative core and supplementary variables. Means based on log-transformed data

EC1						
	V test	Mean in category	Overall mean	sd in category	Overall sd	p value
Permanent.crops	4.056	1.279	0.469	1.276	0.875	0.000
Conserved.forest	2.907	4.233	3.808	0.370	0.641	0.004
Forest age	2.397	3.809	3.170	0.568	1.169	0.017
aspect.degree	-3.102	0.437	1.411	0.806	1.375	0.002
Secondary.forest	-3.801	1.236	2.219	1.110	1.132	0.000
slope.degree	-4.069	1.575	2.159	0.504	0.629	0.000
elevation.meter	-5.025	3.868	4.682	0.619	0.710	0.000
Introduced.grassland	-5.223	1.661	3.011	1.326	1.133	0.000
EC2						
	V test	Mean in category	Overall mean	sd in category	Overall sd	p value
elevation.meter	3.893	5.149	4.682	0.297	0.710	0.000
slope.degree	2.377	2.411	2.159	0.511	0.629	0.017
Forest age	2.195	3.603	3.170	0.552	1.169	0.028
aspect.degree	-4.650	0.331	1.411	0.481	1.375	0.000
EC3						
	V test	Mean in category	Overall mean	sd in category	Overall sd	p value
aspect.degree	6.209	3.072	1.411	0.404	1.375	0.000
Secondary.forest	3.857	3.068	2.219	0.500	1.132	0.000
Carbon.storage	3.367	3.248	2.735	0.478	0.784	0.001
phosphatase	2.961	6.709	6.624	0.145	0.149	0.003
slope.degree	2.195	2.427	2.159	0.446	0.629	0.028
silt_perc	2.076	3.287	3.230	0.152	0.142	0.038
Conserved.forest	-2.295	3.522	3.808	0.579	0.641	0.022
bulk.density	-2.991	0.838	0.858	0.037	0.034	0.003
EC4						
	V test	Mean in category	Overall mean	sd in category	Overall sd	p value
bulk.density	2.297	0.885	0.858	0.044	0.034	0.022
aspect.degree	2.150	2.398	1.411	0.664	1.375	0.032
Introduced.grassland	2.071	3.794	3.011	0.422	1.133	0.038
clay_perc	-2.465	3.145	3.320	0.407	0.214	0.014
phosphatase	-2.604	6.495	6.624	0.179	0.149	0.009
Conserved.forest	-2.809	3.207	3.808	0.996	0.641	0.005
silt_perc	-3.001	3.087	3.230	0.267	0.142	0.003
Forest age	-5.996	0.830	3.170	0.885	1.169	0.000
Carbon.storage	-6.028	1.159	2.735	0.423	0.784	0.000

Figure S.3 Factorial Analysis of Mixed Data (FMDA) on the social-management variables. Blue variables represent the supplementary variables

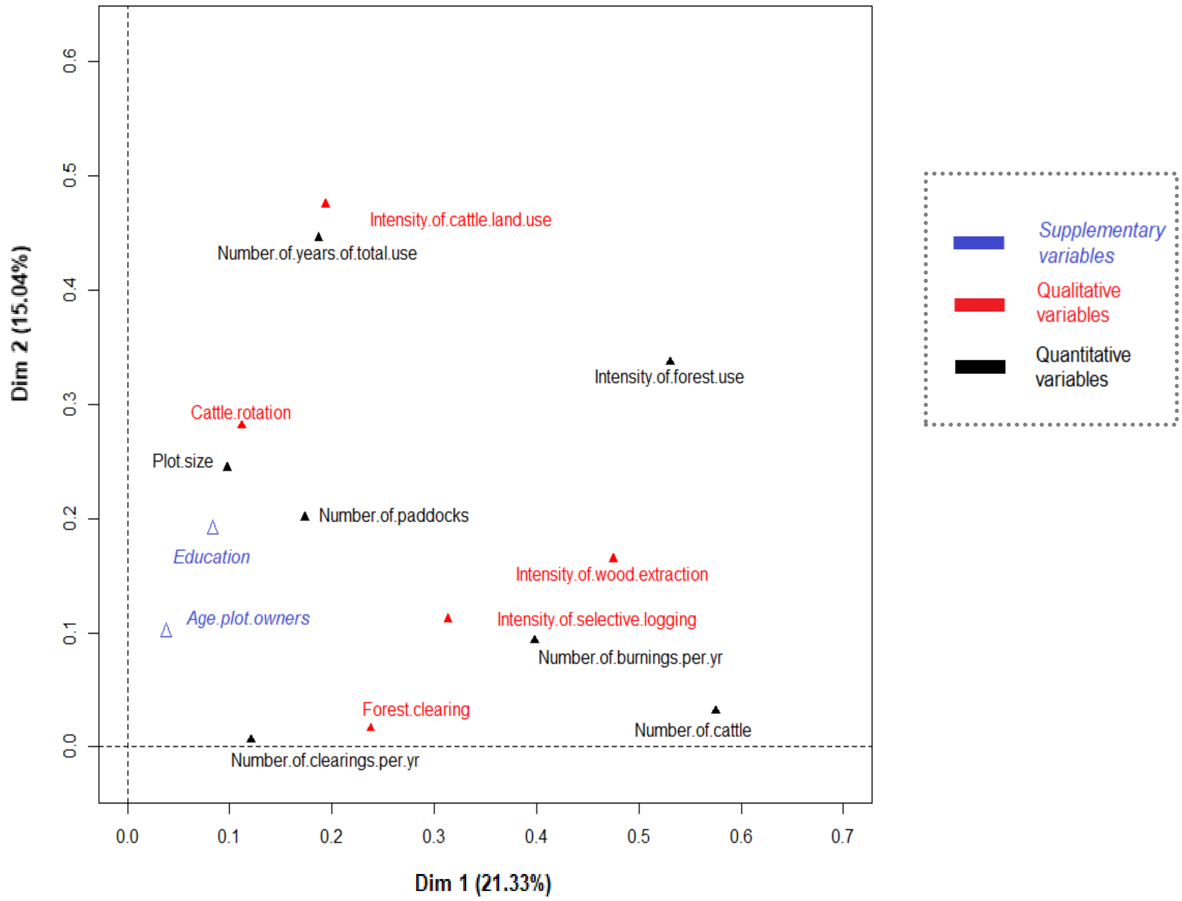


Table S.5 Variance explained per principal component from the FMDA on the Social-management variables

	eigenvalue	percentage of variance	cumulative percentage of variance
comp1	3.4134476	21.334048	21.33405
comp2	2.4062357	15.038973	36.37302
comp3	1.8066516	11.291573	47.66459
comp4	1.4001831	8.751144	56.41574
comp5	1.1565695	7.228559	63.6443
comp6	1.0925251	6.828282	70.47258
comp7	1.0467422	6.542139	77.01472
comp8	0.8005676	5.003547	82.01826
comp9	0.7549515	4.718447	86.73671
comp10	0.5635071	3.521919	90.25863
comp11	0.4882256	3.05141	93.31004
comp12	0.3713889	2.321181	95.63122
comp13	0.2741495	1.713434	97.34466
comp14	0.2355184	1.47199	98.81665
comp15	0.1766792	1.104245	99.92089

Table S.6 Social-management variables contribution per dimension (eigenvalue > 1) on the FMDA. Bold numbers and variables represent the highest values and variables contribution per dimension.

Variables contribution per dimension	Dim.1	Dim.2	Dim.3	Dim.4	Dim.5	Dim.6	Dim.7
Number.of.cattle	**16.8493**	1.2905	3.1410	11.2249	0.0626	0.1273	0.2624
Number.of.years.of.total.use	5.4792	**18.5241**	3.6909	0.5238	2.0003	5.8754	0.3818
Number.of.clearings.per.yr	3.5306	0.2481	15.0341	0.6679	3.1768	1.5533	**4.8573**
Number.of.paddocks	5.0758	8.3501	1.2019	0.6306	**20.8520**	13.1861	0.1417
Number.of.burnings.per.yr	11.6526	3.8681	15.4910	2.2134	0.4703	1.3171	0.0302
Intensity.of.forest.use	15.5470	13.9950	1.1325	3.0389	0.0106	2.8967	0.0006
Plot.size	2.8657	10.1470	**17.4670**	4.6775	1.3364	2.2478	0.4958
Intensity.of.wood.extraction	13.9128	6.8276	**18.1104**	22.7770	2.2388	14.4971	12.5306
Intensity.of.selective.slashing	9.1823	4.6413	9.8827	**26.2720**	9.2189	28.3068	6.9043
Intensity.of.cattle.land.use*	5.6794	19.7444	2.4825	23.0133	56.6650	4.0620	70.1210
Forest.clearing	6.9625	0.6791	11.6258	0.6052	0.0369	9.5998	3.4385
Cattle.rotation	3.2628	11.6847	0.7403	4.3554	3.9314	**16.3306**	0.8359

*Categorical variable redundant with quantitative variable. We considered only the quantitative variable.

Figure S.4 Individuals map (*ejidatarios*) from the social-management clusters (SC)

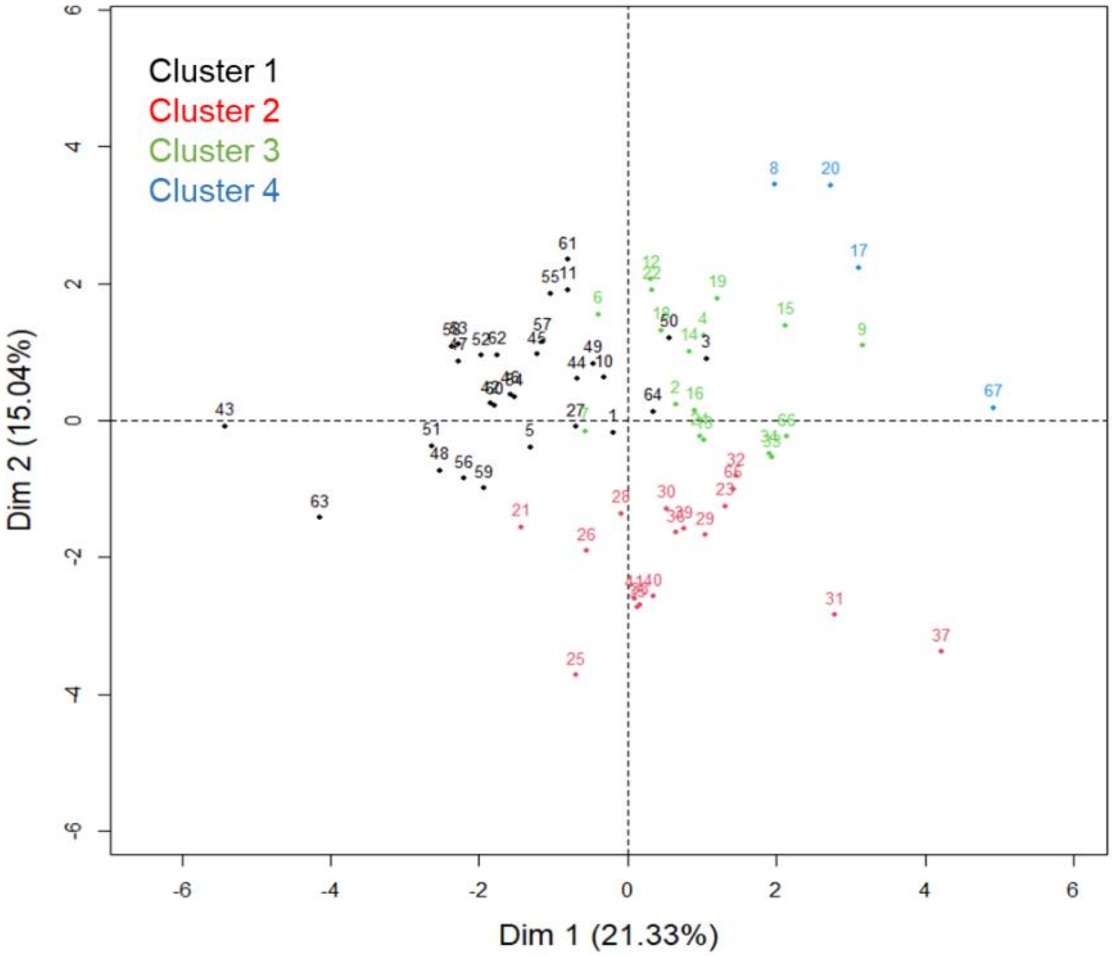


Table S.7 Description of each social-management cluster (SC) by the qualitative variables.

	Cla/Mod	Mod/Cla	Global	p.value	v.test
SC1					
Semi.communal.land=Los Ranchitos	92.30[1]	82.75[2]	38.80	3.16E-11	6.639137
Forest.clearing=no	95.23	68.96	31.34	3.00E-09	5.931611
Intensity.of.wood.extraction=0	68.57	82.75	52.23	1.24E-05	4.370093
Intensity.of.cattle.land.use=2	56.25	62.06	47.76	4.60E-02	1.994954
Education=Elementary	7.69	3.44	19.40	3.52E-03	-2.918119
Intensity.of.wood.extraction=1	14.81	13.79	40.29	1.08E-04	-3.872246
Forest.clearing=si	19.56	31.03	68.65	3.00E-09	-5.931611
SC2					
	Cla/Mod	Mod/Cla	Global	p.value	v.test
Education=Elementary	61.53	47.058824	19.40299	2.50E-03	3.023017
Intensity.of.cattle.land.use=1	61.53	47.058824	19.40299	2.50E-03	3.023017
Forest.clearing=si	34.782609	94.117647	68.65672	7.21E-03	2.686804
Cattle.rotation=si	30.357143	100	83.58209	2.91E-02	2.182568
Cattle.rotation=no	0	0	16.41791	2.91E-02	-2.182568

Intensity.of.cattle.land.use=2	12.5	23.529412	47.76119	2.36E-02	-2.263436
Forest.clearing=no	4.761905	5.882353	31.34328	7.21E-03	-2.686804
Education=Secondary	7.894737	17.647059	56.71642	2.28E-04	-3.685809
Semi.communal.land=Los Ranchitos	0	0	38.80597	4.50E-05	-4.080379
SC3					
	Cla/Mod	Mod/Cla	Global	p.value	v.test
Intensity.of.wood.extraction=1	59.259259	94.117647	40.29851	1.60E-07	5.241016
Forest.clearing=si	36.956522	100	68.65672	5.19E-04	3.47076
Intensity.of.cattle.land.use=3	47.058824	47.058824	25.37313	2.71E-02	2.21028
Cattle.rotation=no	54.545455	35.294118	16.41791	2.82E-02	2.194978
Education=None	0	0	16.41791	2.91E-02	-2.182568
Cattle.rotation=si	19.642857	64.705882	83.58209	2.82E-02	-2.194978
Semi.communal.land=Los Ranchitos	7.692308	11.764706	38.80597	7.79E-03	-2.660837
Forest.clearing=no	0	0	31.34328	5.19E-04	-3.47076
Intensity.of.wood.extraction=0	2.857143	5.882353	52.23881	6.58E-06	-4.506978
SC4					
	Cla/Mod	Mod/Cla	Global	p.value	v.test
Intensity.of.wood.extraction=2	80	100	7.462687	6.52E-06	4.508677
Intensity.of.selective.slashing =2	60	75	7.462687	8.22E-04	3.345299
Cattle.rotation=no	27.272727	75	16.41791	1.29E-02	2.486072
Semi.communal.land=Nacastillo	40	50	7.462687	2.63E-02	2.221723
Intensity.of.wood.extraction=0	0	0	52.238806	4.69E-02	-1.98706
Cattle.rotation=si	1.785714	25	83.58209	1.29E-02	-2.486072
Intensity.of.selective. slashing =0	0	0	83.58209	4.31E-04	-3.52062

[1] 92.3% of the total *ejidatarios* from Los Ranchitos belongs to that SC1.
[2] 82.7% from the individuals in SC1 belong to the *ejido* Los Ranchitos.

Table S.8 Description of each social-management cluster (SC) by the quantitative variables. Means based on log transformed data (log10(n+0.5)).

SC1						
	V test	Mean in category	Overall mean	sd in category	Overall sd	p value
Number.of.years.of.total.use	3.487	3.500	3.089	0.522	0.836	0.000
Number.of.paddocks	-2.668	0.950	1.067	0.282	0.313	0.008
Number.of.clearings.per.yr	-3.054	1.002	1.409	0.998	0.946	0.002
Number.of.cattle	-3.497	3.144	3.624	1.067	0.974	0.000
Number.of.burnings.per.yr	-6.291	0.077	0.788	0.197	0.802	0.000
SC2						
	V test	Mean in category	Overall mean	sd in category	Overall sd	p value
Plot.size	3.677	4.778	4.072	0.595	0.910	0.000
Number.of.burnings.per.yr	3.006	1.298	0.788	0.387	0.802	0.003
Number.of.cattle	2.605	4.160	3.624	0.739	0.974	0.009
Number.of.paddocks	2.422	1.227	1.067	0.156	0.313	0.015
Age.plot.owners	2.158	4.094	3.981	0.098	0.248	0.031
Intensity.of.forest.use	-2.433	1.002	1.224	0.406	0.433	0.015
Number.of.years.of.total.use	-5.960	2.038	3.089	0.742	0.836	0.000

	V test	Mean in category	Overall mean	sd in category	Overall sd	p value
SC3						
Number.of.burnings.per.yr	3.613	1.400	0.788	0.752	0.802	0.000
Number.of.clearings.per.yr	2.959	2.000	1.409	0.824	0.946	0.003
Intensity.of.forest.use	2.694	1.471	1.224	0.170	0.433	0.007
Plot.size	-3.148	3.467	4.072	0.811	0.910	0.002
SC4						
	V test	Mean in category	Overall mean	sd in category	Overall sd	p value
Intensity.of.forest.use	3.544	1.974	1.224	0.119	0.433	0.000

Figure S.5 Correlation circle from the PCA on the social-ecological variables (governance variables). Blue variables represent the supplementary variables: ecological clusters (EC) and social clusters (SC) per ejido

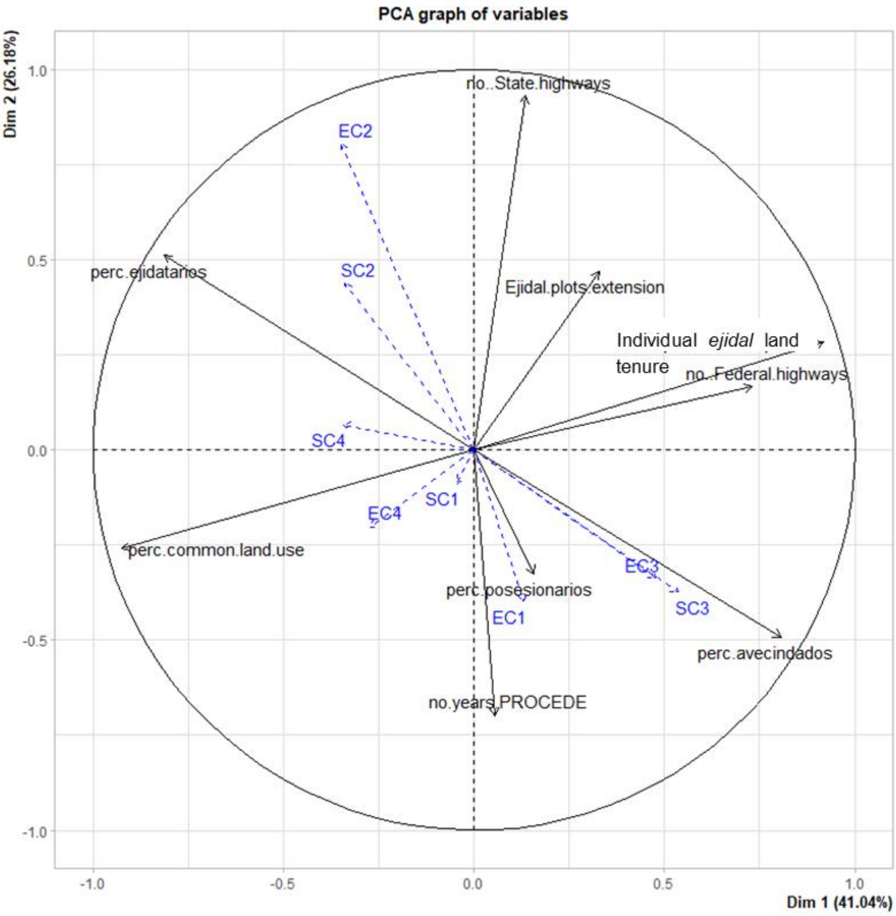


Table S.9 Variance explained per principal component from the PCA on the social-ecological variables (governance variables)

PCA-sesus	eigenvalue	percentage of variance	cumulative percentage of variance
comp1	3.694	41.041	41.041
comp2	2.356	26.175	67.216
comp3	1.787	19.859	87.075
comp4	0.750	8.330	95.405
comp5	0.319	3.544	98.949

comp6	0.090	1.001	99.949
comp7	0.004	0.050	99.999
comp8	0.000	0.001	100.000

Table S.10 Social-Ecological (governance) variables contribution per dimension (eigenvalue > 1) on the PCA. Bold numbers and variables indicate the highest values and variables contribution per dimension

Variables contribution per dimension	Dim.1	Dim.2	Dim.3
Ejidal.plots.extension	2.934	9.296	**31.851**
no.years.PROCEDE	0.079	**20.693**	24.811
perc.individual.land tenure	**22.771**	3.390	1.495
perc.common.land.use*	23.125	2.874	1.000
perc.ejidatarios	17.886	11.076	2.607
perc.avecindados	17.581	10.321	3.662
perc.posesionarios	0.665	4.508	25.177
no..Federal.highways	14.464	1.178	8.984
no.State.highways*	0.496	36.664	0.413

*There were no significant differences among clusters; therefore, we kept as explanatory variable the next highly weighted variable in that dimension

Figure S.6 Individuals map (*ejidos*) from the social-ecological system units (SESU)

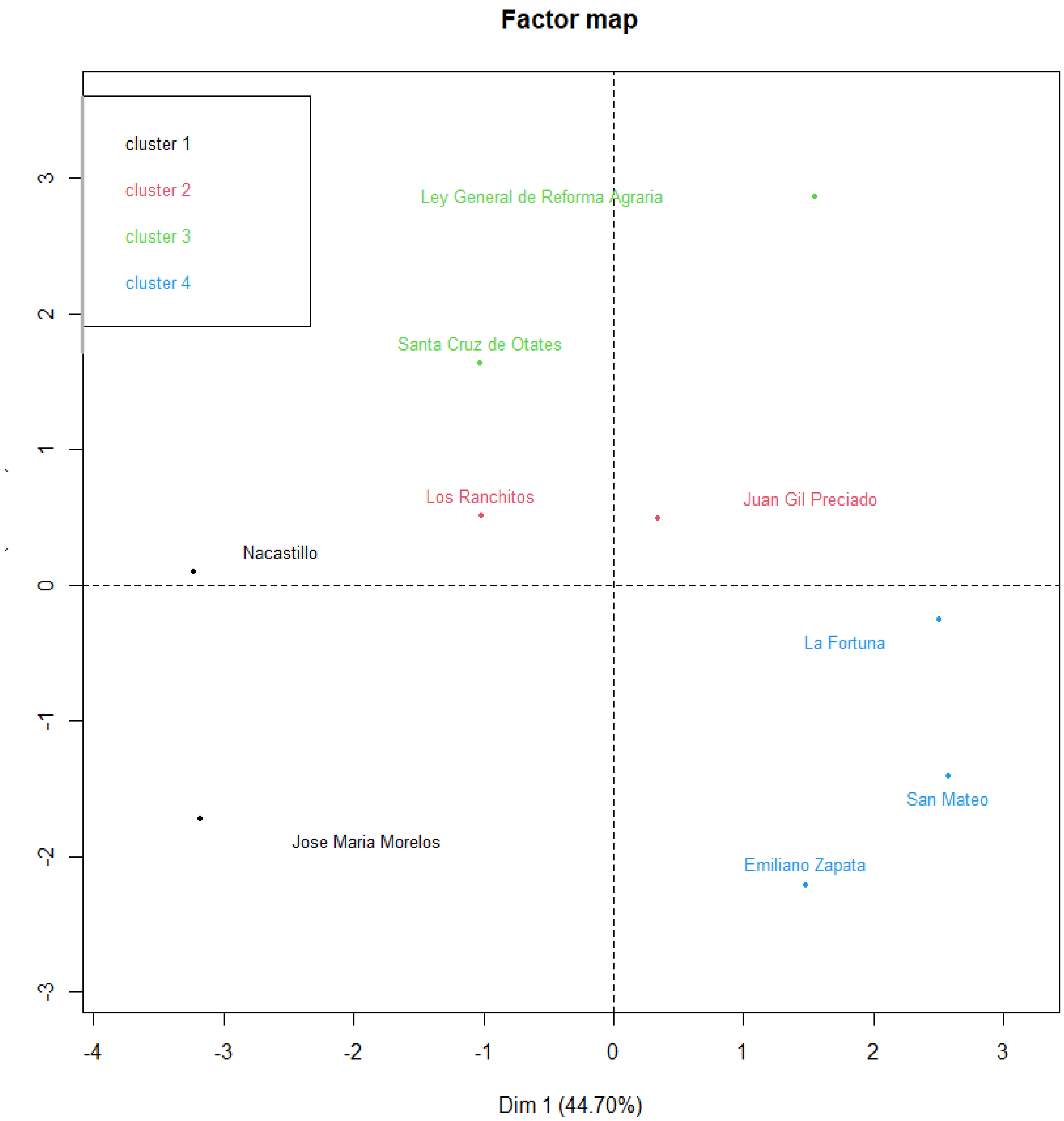

Factor map
cluster 1
cluster 2
cluster 3
cluster 4
Ley General de Reforma Agraria
Santa Cruz de Otates
Los Ranchitos
Juan Gil Preciado
Nacastillo
La Fortuna
San Mateo
Jose Maria Morelos
Emiliano Zapata
3
2
1
0
-1
-2
-3
-4
-3
-2
-1
0
1
2
3
Dim 1 (44.70%)

Table S.11 Description of social-ecological system units (SESU) by the quantitative core and supplementary variables.

	V test	Mean in category	Overall mean	sd in category	Overall sd	p value
SESU1						
perc.common.land.use	2.556	99.356	37.047	0.080	36.859	0.011
perc.surface.plotted	-2.551	0.000	60.850	0.000	36.067	0.011
SESU2						
	V test	Mean in category	Overall mean	sd in category	Overall sd	p value
Ejidal.plots.extension	2.261	27.350	16.656	2.750	7.150	0.024
SESU3						
	V test	Mean in category	Overall mean	sd in category	Overall sd	p value
EC2	1.981	70.000	36.272	10.000	25.737	0.048
no.years.PROCEDE	-2.465	18.000	22.889	0.000	2.998	0.014
SESU4						
	V test	Mean in category	Overall mean	sd in category	Overall sd	p value
perc.avecindados	2.718	72.615	29.514	5.838	31.713	0.007
SC3	2.012	64.287	36.490	25.421	27.637	0.044
EC2	-2.079	9.523	36.272	13.468	25.738	0.038
perc.ejidatarios	-2.698	24.310	67.212	4.258	31.800	0.007

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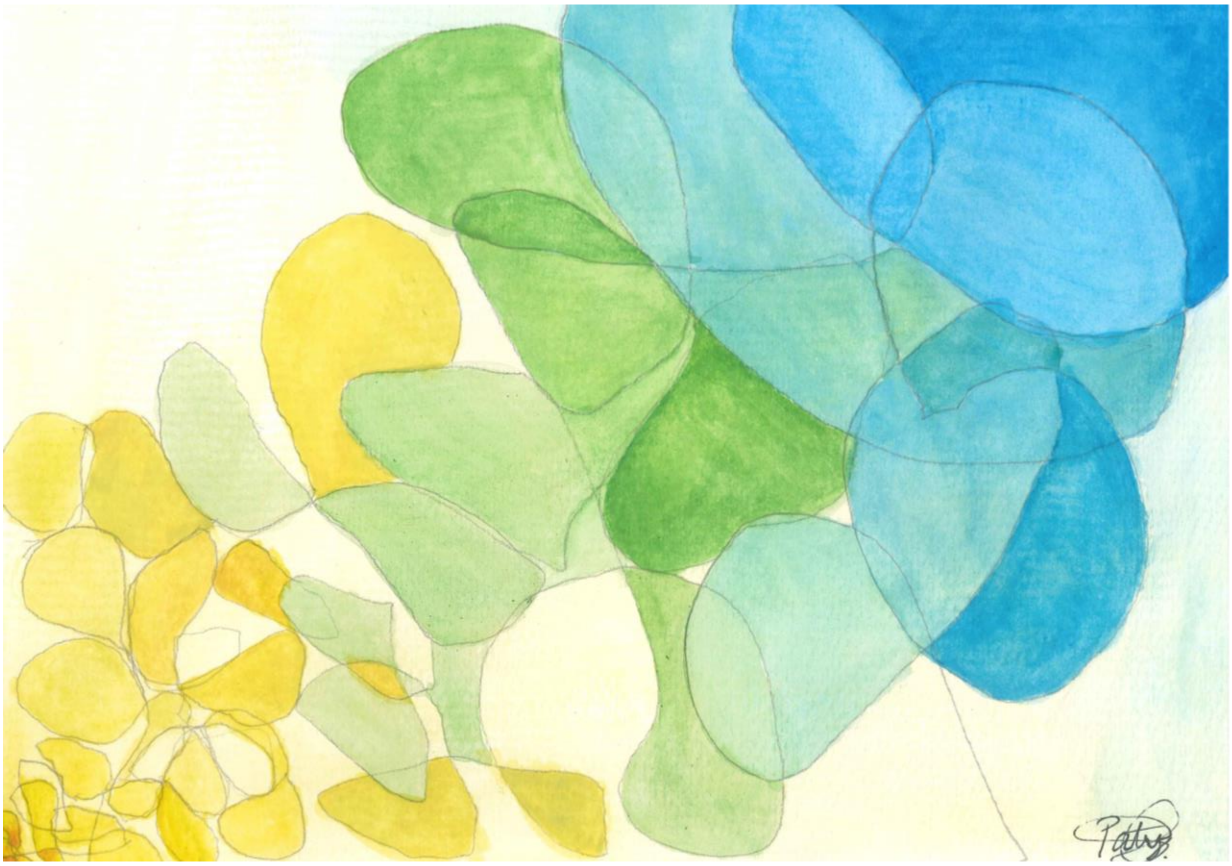
CHAPTER IV. THE MORE YOU HAVE, THE MORE YOU WANT: HOW LAND TRANSFORMATION, MANAGEMENT INTENSITY AND GOVERNANCE AFFECT QUALITY OF LIFE



"*The more you have, the more you want"* Patricia Santillán Carvantes. May 2023

Journal: Sustainability sciences

Title: The more you have, the more you want: the roles of land transformation, management intensity, and governance affect the quality of life.

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Abstract

Achieving good quality of life while conserving nature is a major socio-ecological challenge. This is particularly important for smallholders living in biodiversity hotspot areas. This paper explores how smallholders inhabiting tropical dry forests (TDF) in Mexico perceive their QoL and how it changes across a suite of SES experiencing different land transformation dynamics, management intensity, and governance practices. Specifically, we aim to: 1) identify the dimensions of QoL that smallholders perceive, 2) understand how these QoL dimensions change across SES, and 3) examine how an objective measure of welfare (Current Welfare Index) and smallholders' perceptions of fulfilled material and non-material needs varied across SES. We analyzed the content of 25 in-depth interviews with farmers and identified 48 QoL items belonging to six categories: 1) social capital, 2) economic capital, 3) agency, 4) nature, 5) pleasant non-work activities, and 6) governmental services and two additional dimensions referred to obstacles and enablers of QoL. We found that the more land transformed, the more enablers and obstacles of QoL were identified and the more emphasis on economic capital to achieve QoL. As management is intensified and governance fosters individualism, the higher the Current Welfare Index and the lower the self-perceived material and non-material satisfaction. We discuss the need for governance structures promoting smallholders' worldviews that move beyond utilitarianism and foster commons.

Introduction

A major obstacle to sustainability is understanding smallholders' quality of life (QoL) (Tonon and Rodríguez de la Vega 2016, UN 2016). Smallholders in the Global South significantly contribute to global agriculture and food production (FAO 2014). However, they also are struggling with several issues, including undiversified production structures, welfare gaps, challenges in the labor market, and increased violence and crime (Bartra 2002). Despite this, in places such as Latin America, the reported subjective wellbeing is higher concerning their income levels than other nations worldwide (Tonon and Rodríguez de la Vega 2016). Thus, it is essential to comprehend smallholders' QoL, identify the variables that contribute most to determining their QoL, and involve them in decision-making by highlighting the diversity of viewpoints (Bartra 2002, Tauro et al. 2018).

Quality of Life has been described as the difference between people's aspirations and perceived resources to accomplish them (McGregor et al. 2009). Early in the 1990s, Fitoussi and Rosanvallon (1997) emphasized that historically, the assessment of QoL had given preference to the consideration of income, particularly salaries. Then, using assessments appropriate for the culture, national programs began to standardize and quantify the so-called wellbeing (for differences between QoL and wellbeing, see Gasper 2010). For instance, national 'barometers,' such as the Australian Unity Wellbeing Index (McGregor et al. 2009), or the developing QoL notion of Buen Vivir ('living well') in Latin America make use of quantitative methods to measure QoL that are rooted in the local culture (Guardiola and García-Quero 2014, Sterling et al. 2017). Moreover, national programs, such as Bhutan's Gross National Happiness Index, go beyond QoL based mainly on income and attempt to measure a holistic QoL (Sterling et al. 2017). Despite these measurements, research and policy still fall short in identifying the QoL dimensions and their satisfaction levels in the local contexts.

Identifying fundamental human needs and their satisfaction level has been the object of many QoL studies (Doyal and Gough 1991, Diener 1994, Tonon and Rodríguez de la Vega 2016). For example, Doyal and Gough (1991) present a thorough and all-encompassing theory of human needs concluding that only two fundamental human needs—health and autonomy—should be acknowledged. Knowing that human needs and their satisfaction may change concerning the context of the people, there are various indexes to unravel and gauge QoL. For instance, the Global Person Generated Index (GPGI) (Ruta et al. 1994) determines a person's satisfaction level in the areas of life that are most significant to them using a combination of open-ended questions, scoring, and point distribution. (Diener (1994) developed a satisfaction scale to interpret the type and level of satisfaction. The range goes from high and very high satisfaction, people who love their lives and feel that things are going very well; to medium, people generally satisfied but with areas that would like to develop further; low, people with small but significant problems; and unsatisfied and extremely unsatisfied, are people that present chronic levels of dissatisfaction with their lives. Diener's method requires inquiring about the quality of life from the affective, such as the feelings of the moment, and from the cognitive, such as achievements and satisfaction (McGregor et al. 2009, Tonon and Rodríguez de la Vega 2016). Another example is the WeDQoL, which is an individually weighted measure of QoL by obtaining scores that reflected not only the general perspective of people in each country but also the priorities of each person completing the measure taking into consideration their specific geographical and social position (McGregor et al. 2009). When the WeDQoL was applied in Northeast and Southern Thailand, McGregor et al. (2009) found that socioeconomic status was highly significant concerning what people aspired to and the degree to which they felt these aspirations had been achieved, while rural or urban location, gender, and age were relatively unimportant. Different visions of QoL may lead to different relationships with nature (Tauro et al. 2018). Therefore, to advance the understanding of fundamental needs, their satisfaction level, and the relationship with nature, the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) has made a call to develop research that sheds light on how disparate visions of QoL can motivate different conservation goals and sustainable uses of nature (Díaz et al. 2015).

Overall, there is consensus on the inextricable link between nature and people's QoL (MA 2005, Díaz et al. 2015). These have been assessed through the concepts of ecosystem services (MA 2005) and Nature's Contribution to People to explore the types of benefits obtained (NCP, Díaz et al. 2018). Some have hypothesized that more interaction with nature will lead to happier and healthier people (Annerstedt and Währborg 2011, Russell et al. 2013), and yet, there are global observations that show an increase in human wellbeing with declining trends of biodiversity and NCP (MA 2005, Raudsepp-Hearne et al. 2010). The so-called "environmentalist's paradox" hypothesized that incomplete QoL measures could explain this contradiction, as well as the excessive focus on material dimensions of QoL or the fulfillment of QoL through technological innovations (Raudsepp-Hearne et al. 2010). In this spirit, the approach of social-ecological systems explains that the human-nature relationship is shaped by ecological, social, cultural, and governance factors across scales (SES; Berkes et al. 1998, Chapin et al. 2009, Ostrom 2009, Martín-López et al. 2017). How these drivers determine how people make decisions and manage the land to fulfill their material and non-material needs varies across social-ecological contexts (Norström et al. 2022). To date, large knowledge gaps remain at the interface between QoL (objective and subjective) and the different social-ecological contexts (Mastrángelo et al. 2019), particularly in Latin America.

Latin America has many hotspots for biodiversity (Toledo 1999), which is a major challenge for achieving a good QoL because land cover transformation for productive activities affects not only biodiversity but also the smallholders' QoL (Nagendra 2018). Tropical dry forests (TDF) are considered biodiversity hotspots and, at the same time, they are one of the most threatened ecosystems in the world (Janzen 1988, Sánchez-Azofeifa et al. 2005, Portillo-Quintero et al. 2015). Smallholders are the stewards and managers of a large fraction of the biodiversity and productive lands in different parts of the world (Boege 2009, Graeub et al. 2016, Bellon et al. 2021). However, most of the studies in TDF analyze the effects of land management on biodiversity and consider smallholders as the main ones responsible for biodiversity loss without integrating a comprehensive analysis of the impact of land management on their QoL (Trejo and Dirzo 2000, Sánchez-Azofeifa et al. 2009, Trilleras et al. 2015, Sánchez-Romero et al. 2021). Considering the perceptions and needs of smallholders in TDF according to the different social and ecological conditions is most urgently needed (Quijas et al. 2019). Specifically, studies that explore the impact of the social-ecological characteristics, such as land cover transformation, land management intensity, and governance, on smallholders' QoL are particularly scarce.

This research explores how smallholders inhabiting a TDF in Mexico perceive their QoL and how those perceptions change across SES with different land transformations, management intensity, and governance. Specifically, we aim to: 1) identify the dimensions of QoL that smallholders perceive, 2) understand how these QoL dimensions change across SES, and 3) examine how an objective measure of welfare (Current Welfare Index) and smallholders' perceptions of fulfilled material and non-material needs varied across SES.

Methods

Case study

The Chamela-Cuixmala region is part of the TDF biome along the Mexican Pacific coast (Ceballos and García 2010). The region comprises the Chamela-Cuixmala Biosphere Reserve and its transition area (UNESCO 2022), located in the municipalities of La Huerta and Villa Purificación in Jalisco, Mexico. The ownership regime is a critical factor affecting the transition areas' landscape configuration. Most of the land (70-80%) is under a governance unit specific to Mexico, called *ejido*, a semi-communal land tenure regime that emerged from the land redistribution policies following the Mexican Revolution of the 1910s (Castillo et al. 2005, Monroy-Sais et al. 2018, Pingarroni et al. 2022, Fig.1). Local collective management arrangements have been developed in many *ejidos*, and are operationalized through an *ejidal* assembly (Toledo 1996, Agrawal 2007, Schroeder and Castillo 2013). Land tenure within *ejidos* in this region can occur in three ways (Schroeder and Castillo 2013). First, *ejidatarios*, or the landholding members of the *ejido*, can inherit the land right (*ejidal* plots), sell it, and vote in the *ejidal* assembly to take communal decisions. *Ejidatario* has rights over communal lands within the *ejido*. Second, *posesionarios* possess land within the *ejido* but cannot pass it to the following generation. *Posesionarios* do not hold rights over communal lands and cannot vote in the *ejidal* assembly. Each *ejido* determines the level of *posesionarios* participation in collective management. Finally, *avecindados* are those who have settled within the *ejido* for more than a year and possess neither land rights nor vote in the Assembly (Schroeder and Castillo 2013). Traditionally, men hold most of these three types of land rights and make land-related decisions, although there are few "*ejidatarias*" (women). In this work, we have worked only with *ejidatarios* (i.e., men smallholders) in the surrounding areas of the Chamela-Cuixmala biosphere reserve.

Ejidatarios within *ejidos* surrounding the Chamela-Cuixmala biosphere reserve are aligned with the extensive cattle ranching and silvopastoral culture (Tauro et al. 2021). Cattle ranching is strongly limited by biophysical aspects, such as water availability, and economic ones, such as financial resources to invest in cattle maintenance (Maass et al. 2005). Based on the biophysical conditions (i.e., topography, soil fertility, carbon stock, etc.), land transformation (i.e., land cover), land management intensity (i.e., cattle rotation, number of cattle, number of wood extraction, etc.), and governance characteristics (i.e., individual land tenure by *avecindados*, or communal land tenure by *ejidatarios*) Santillán-Carvantes et al. (In press) have identified four social-ecological system units (SESU) in the area (Fig. 1). The four SESU showed a geographical gradient from the center of the country (SESU1) towards the coast (SESU4) that align with topographical and climatic conditions. Moreover, the different SESU represented a gradient of land cover transformation (from SESU1, the least transformed, to SESU4, the most transformed), management intensity (from SESU2, which is the most extensively managed to SESU4 that is the most intensively managed), and governance systems (from SESU1 that mostly implemented communal governance to SESU4, which governance system mostly rely on private land and individual land tenure) (Fig. 1).

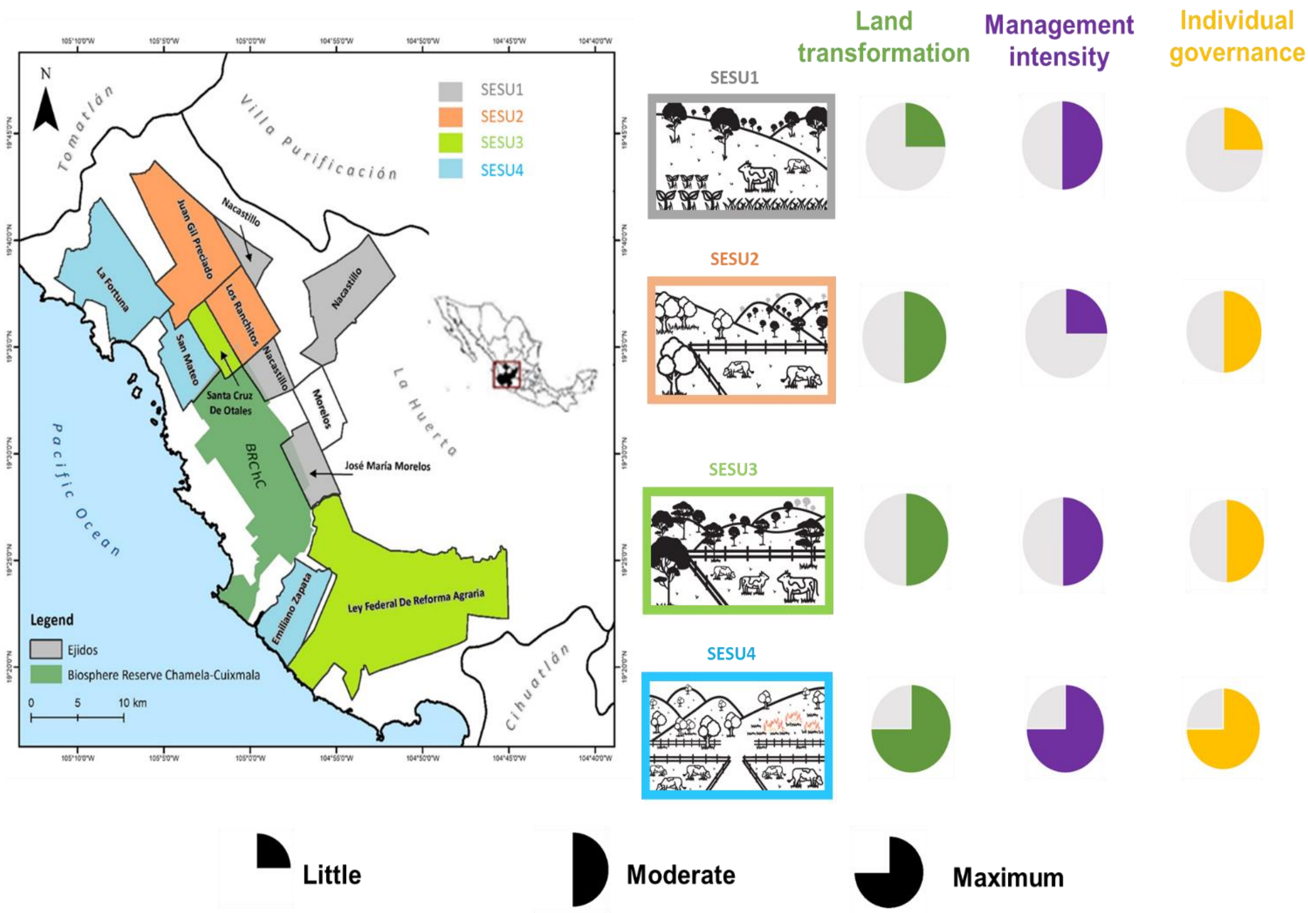


Figure 1. Location of the Chamela-Cuixmala region, comprised of the Biosphere Reserve Chamela-Cuixmala (BRChC; dark green color) and the transition areas at the governance units (*ejidos*) in the adjacent area in the Municipality of La Huerta and Villa Purificación, Jalisco, Mexico. Different colors of the *ejidos* denote different Social-Ecological System Units (SESU, Santillán-Carvantes et al. in press). The area covered by the colored circles denotes the intensity of land transformation, management intensity, and individual governance in each SESU.

Data collection

To study the smallholders' perceptions of QoL in the Chamela-Cuixmala region, we used 25 face-to-face, semi-structured in-depth interviews performed between February and June 2015 (Tauro et al. 2018). Table 1 presents the interview's guiding questions to unravel the respondents' current and desired QoL. The participants were selected according to their representation in the *ejidal* assembly and their capital invested in cattle. Two to seven *ejidatarios* were interviewed per *ejido*.

Responses were analyzed through content analysis following the QoL dimensions proposed by Rogers et al. (2012) and Fagerholm et al. (2020): *Material living standards, Health, Physical and economic security, Ecosystems, Education, Work and leisure, Agency and political voice,* and *Social relationships*. *Material living standards* were related to housing, food, and public and private services (i.e., having a car). *Health* was related to medical visits or self-perceptions of their health. *Physical and economic security* was related to economic capital and the sense of physical security (i.e., non-violent contexts). The dimension of *ecosystems* was related to the biotic or abiotic factors within an ecosystem (i.e., water, cattle, or geographic features) that contribute to their QoL. *Education* was related to access to school or learning activities. The dimension of *work* was related to having a meaningful occupation and the security of having an income, while the dimension of *leisure* referred to the satisfaction gained with outdoor activities such as tourism, hiking, or birdwatching. *Agency and political voice* were related to the perceptions of having a voice in decision-making, trust in government, free mobility, and freedom of choice. *Social relationships* were related to social interactions, community, sense of place, traditions, generations, and religious activities. A response could be coded with several QoL dimensions. For example, the response to how you *feel today with your life*: "*I feel well and complete, with my family complete, I work independently, with no schedule. I feel healthy and strong*" (S4) was interpreted as social relationships, a sense of plenitude, good health, and agency with the sense of freedom. After the first classification of the responses, we developed a locally relevant classification of the QoL dimensions. In this process, we merged items and added new inductively revealed dimensions. We finally used six dimensions of QoL -i.e., social capital, economic capital, agency, nature, pleasant non-work activities, government, and services-. In addition, we identified those obstacles and enablers that affect the smallholders' QoL. The authors inductively coded these two last ones due to the inherent difference in conception between the perceived items of QoL and obstacles and enablers mentioned by the interviewees.

Table 1. Questions included in the interviews with smallholders to unravel the current and desirable QoL.

Questions on the current quality of life	Questions on desirable quality of life
How do you feel today with your life? Explain why	What is a good life?
Do you feel satisfied with your life?	What are your wishes for a good life in 10 or more years?
What do you do to have a "good life"?	For you to be better, what would you change and why?
For you to be better, what would you keep the same and why?	

Change in perceptions across the Social-Ecological System Units (SESU)

Each of the 25 interviewees was associated with one of the four SESU (5-6 *ejidatarios* interviewed per SESU Table S2). We estimated the average number of times the interviewees per SESU mentioned a QoL dimension. For those QoL dimensions for which the data followed normal distributions (checked with the Shapiro-Wilk test (Shapiro and Wilk 1965), we tested for differences among SESU by using ANOVA. When variables of the QoL dimensions did not follow a normal distribution, we ran Kruskal-Wallis tests. Post hoc tests were implemented when significant differences among SESU were identified, using a Tukey test (given that only normal data presented significant differences). To test for differences between current and desirable QoL, we used a t-test and a Mann-Whitney test. All the analyses were carried out using R version 4.0.5 (R core Team 2014). We used the packages "car" (Fox and Weisberg 2019) for the ANOVAs, and the package "multcomp" (Hothorn et al. 2008) for the post hoc tests. The t-test and Mann- Whitney test were part of the general commands of R.

Current Welfare Index and fulfillment of material and non-material needs

We constructed a Current Welfare Index to indicate material needs satisfaction level. We constructed it based on variables that were highlighted during the interviews: diversity of income sources, assistance to the doctor in the last year, number of land rights, number of owned plots, facility of access to water, number of cattle, number of federal support programs that they receive, and if they received remittances or not (Table 2). The current welfare index ranges from zero to one; zero means that material needs are not fulfilled, and one means that they are completely fulfilled. We normalized the indicators to facilitate their interpretability (Table 2). Then, we calculated the mean of all the variables per smallholder to have a final score per person, as shown in Equation 1. We performed an ANOVA test to detect differences in the Current Welfare Index across SESU.

Equation.1 $$Current\ Welfare\ Index\ = \frac{(\sum_1^n\ \ (X1+X2+\cdots Xn))}{n}$$

Where X_1, X_2, and X_n are the scores for the different variables, and n is the number of variables.

Table 2. Response curves used to transform each variable representing the fulfillment of material needs, and that is used to calculate Current Welfare Index. X_{max} is the maximum value observed for that variable, and X_{min} is the minimum value observed.

Variable	**Type of response curve**	X_{max}	X_{min}	X_{mean} (± SD)	**Scoring formula**
Diversity of income sources	More is better	4	1	1.8 (0.86)	X_n / X_{max}
Assistance to the doctor in the last year	Less is better	3	0	1.36 (0.99)	$(X_{max}-X_n)/X_{max}$
Number of land rights	More is better	2	1	1.08 (0.27)	X_n / X_{max}
Number of owned plots	More is better	11	1	3 (2.5)	X_n / X_{max}
Facility of access to water (categorical: easy=1, medium=0.5, difficult=0)	Easily accessible is better	-	-	-	-
Number of cattle	More is better	300	4	66.68 (68.21)	X_n / X_{max}
Number of federal programs support that they receive	More is better	2	0	0.96 (0.61)	X_n / X_{max}
Remittances (categorical: yes=1, no=0)	Yes is better	-	-	-	-

Finally, in the content analysis, we distinguished whether or not the smallholders referred to material or non-material needs and whether those were fulfilled or not. Sometimes, the same answer could mean both "fulfilled" and "unfulfilled" for different dimensions of QoL. For example, the response "*life is a function of external forces, I feel disappointed, insecurity generates my concern. Something is not working well, but you do not have to make your life miserable for that. Besides, I feel happy; I have my family*" (S20). In this case, the QoL dimension of public security is not fulfilled, while the QoL dimension referring to having a family (i.e., a small community) was perceived as fulfilled. Nevertheless, both refer to non-material needs and therefore, this statement was coded as both fulfilled and unfulfilled non-material needs. Moreover, one statement could refer to the material and non-material needs as illustrated by the following answer: "*Very good, I feel complete, my family is complete, I work independently, there is no schedule, I am healthy*" (S4). In these cases, we coded the answer as material and non-material, and in this particular case, as fulfilled material and non-material needs. Four variables were created from this content analysis: fulfilled and unfulfilled material needs and fulfilled and unfulfilled non-material needs. We then calculated their mean and standard deviation for each SESU and tested for significant differences among SESU using ANOVA and Kruskal Wallis tests.

Results

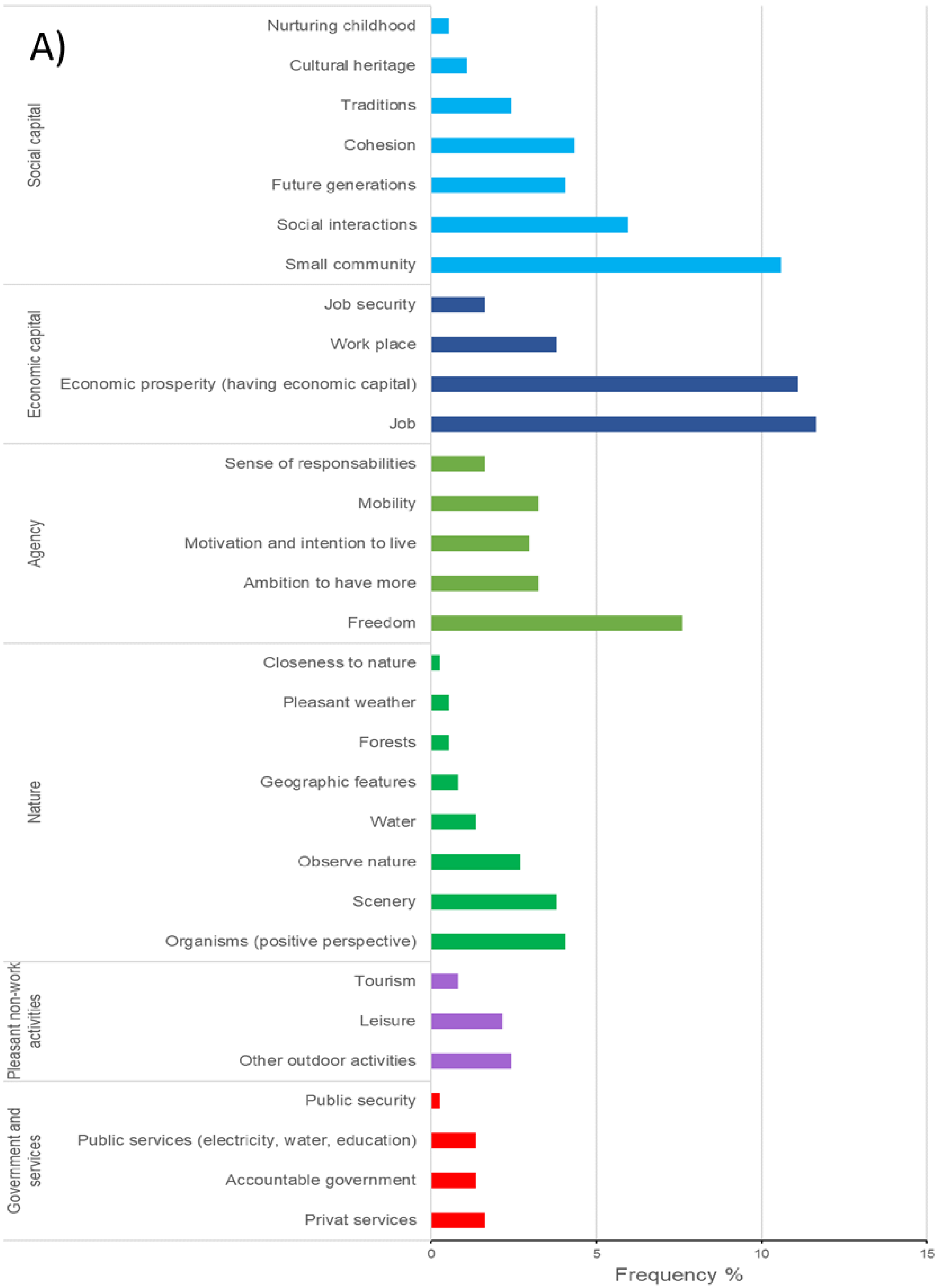
Dimensions of quality of life

The interviewed smallholders distinguished 48 different items related to QoL, which were organized into six dimensions of QoL –i.e., social capital, economic capital, agency, nature, pleasant non-work activities, and government and services (Fig. 2A) - and into obstacles and enablers of achieving a good QoL (Fig. 2B).

Social capital and economic capital were the two most prominent dimensions of QoL (29% and 28% of all mentions, respectively, Fig. 2A). For social capital, social interactions and belonging to a small community were the most highly mentioned (6% and 11%, respectively, Fig. 2A). For example, people often pointed out the importance of the family in their lives as illustrated by the following quote: "*I feel calm because my daughter supports me on my medical visits*" (S5, the complete details of the smallholders interviewed are found in table S3). Regarding economic capital, most respondents referred to economic prosperity and job aspects, as illustrated by the quote: "*Good, I have work and a source of income*" (S12). When referring to the job, some respondents expressed the satisfaction of having a meaningful occupation, as the following quote illustrates "I feel satisfied; I achieved everything I wanted in my work" (S25). The fourth most expressed item referred to the sense of freedom (7.5% of statements), which represents the dimension of agency, often related to the freedom in their job, as illustrated by the following quote "*I work independently with no schedule*" (S4). Table S1 provides more examples of *verbatims* that represent the different items of QoL in each dimension.

We found that the most prominent obstacles to achieving a good QoL were the sense of decadence (13% of all mentions; Fig. 2B). This obstacle referred to the sense that there is no more space for wishes, as illustrated by the quote, "*There is no more good life to live in plenitude for people with 50 or 60 years old, there is no space for wishes*" (S19) and "*I feel wasted, I cannot work because I get tired soon*" (S9). The second most important obstacle represented the interviewee's awareness of their self-limitations (9.8%; Fig. 2B), for example, as illustrated in the quotes "*We have to be aware of what God brings to us"* (S18) and "*I did not know how to take advantage of the opportunities that I had"* (S3).

The most prominent enablers of a good QoL included: good health, good food, tranquillity, and happiness (10%, 9.8%, 9.8%, and 8.7%, respectively; Fig. 2B). The quotes "*Thank God, the world owes me nothing, I asked God that my family does not get sick and he gave it to me"* (S22), "*Good, I have work, and we eat nicely"* (S2), and "*I feel satisfied and happy, I achieve everything I wanted in my job"* (S25) are examples representing those enablers. Table S1 presents a selection of quotes for the obstacles and enablers.


A)
Social capital
Nurturing childhood
Cultural heritage
Traditions
Cohesion
Future generations
Social interactions
Small community
Economic capital
Job security
Work place
Economic prosperity (having economic capital)
Job
Agency
Sense of responsabilities
Mobility
Motivation and intention to live
Ambition to have more
Freedom
Nature
Closeness to nature
Pleasant weather
Forests
Geographic features
Water
Observe nature
Scenery
Organisms (positive perspective)
Pleasant non-work activities
Tourism
Leisure
Other outdoor activities
Government and services
Public security
Public services (electricity, water, education)
Accountable government
Privat services
0
5
10
15
Frequency %

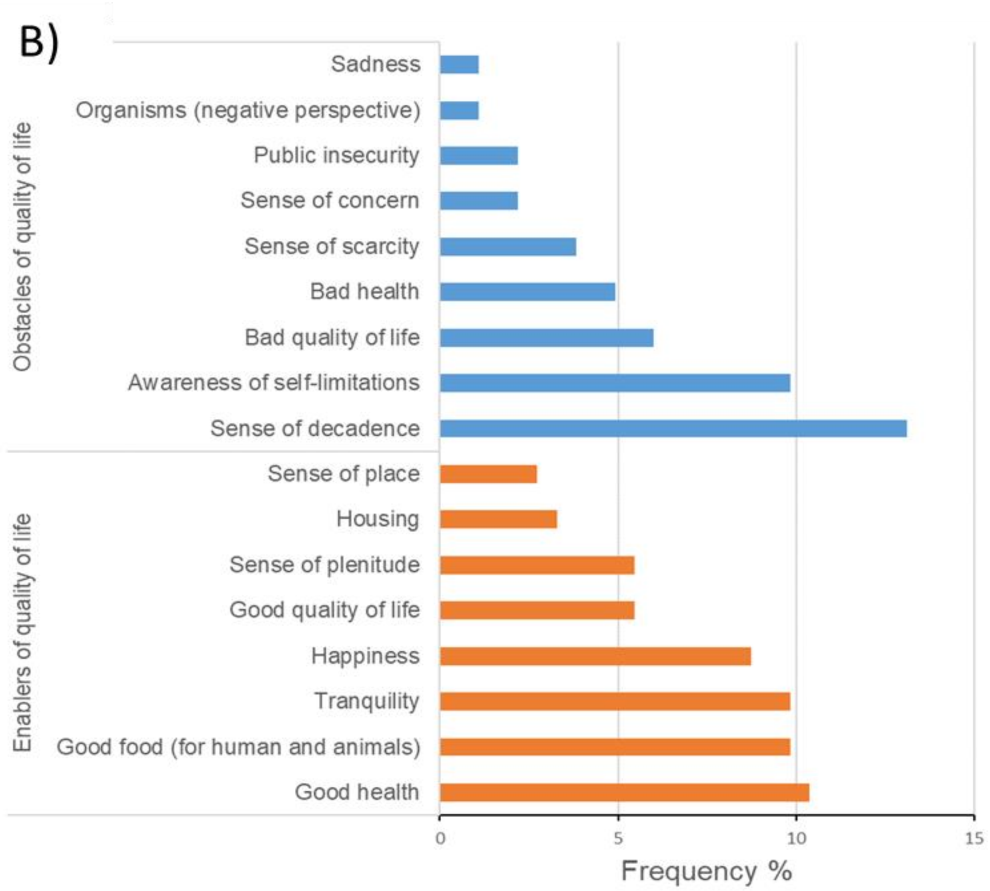


Figure 2. Relative frequency of (A) perceived 31 items of QoL, and (B) 17 items of obstacles and enablers of QoL perceived by the 25 smallholders interviewed in the Chamela-Cuixmala region. The proportion of (A) was calculated from the total of 31 items mentioned (369), and the proportion of (B) was calculated from the total of 17 items mentioned (183).

Change in current and desirable QoL across the Social-Ecological System Units (SESU)

The dimensions of QoL, and the obstacles and enablers of QoL, differed among SESU for both current (Fig. 3) and desirable (Table 3) conditions. As land transformation increased (from SESU1 to SESU4), the obstacles and enablers were more frequently mentioned in both current (obstacles: X^2 = 4.53, df = 3, p-value = 0.209; enablers: X^2 = 1.47, df = 3, p-value = 0.687) and desirable conditions of QoL (obstacles: X^2 = 2.86, df = 3, p-value = 0.413; enablers: *F-statistic* =2.365, df = 3, p-value = 0.1) (Table S4). As management intensity increased (from SESU2 to SESU4), nature was more frequently mentioned, and social capital was less frequently mentioned as desirable (Table 3; Table S4). As governance fostered communality (from SESU1 decreased to SESU4) and land transformation decreased, pleasant non-work activities were frequently mentioned as desirable (SESU1, Table 3).

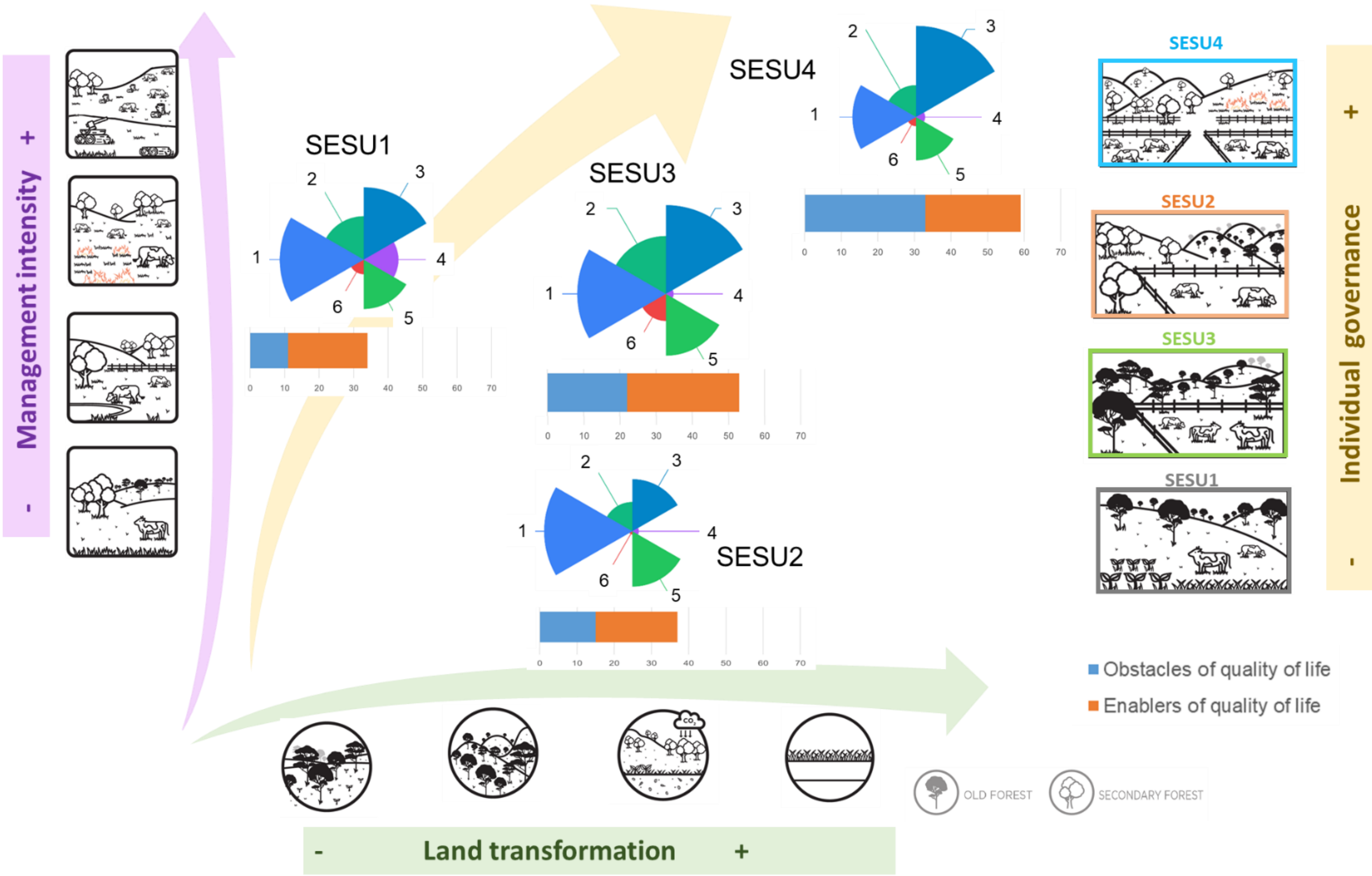
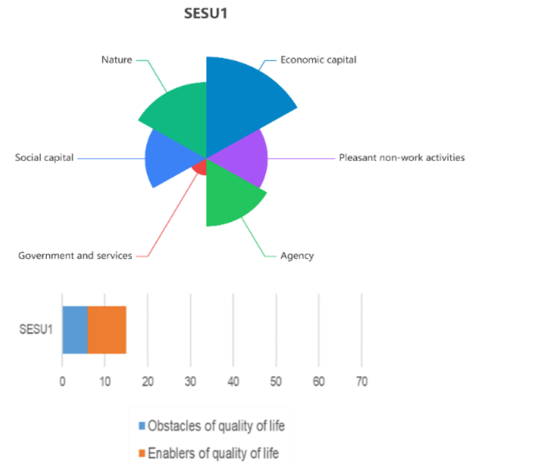
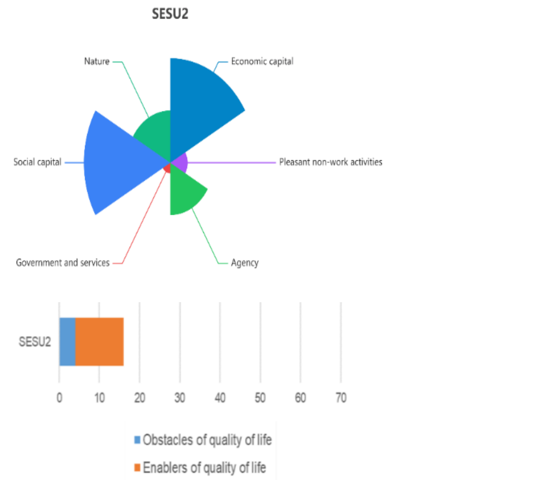
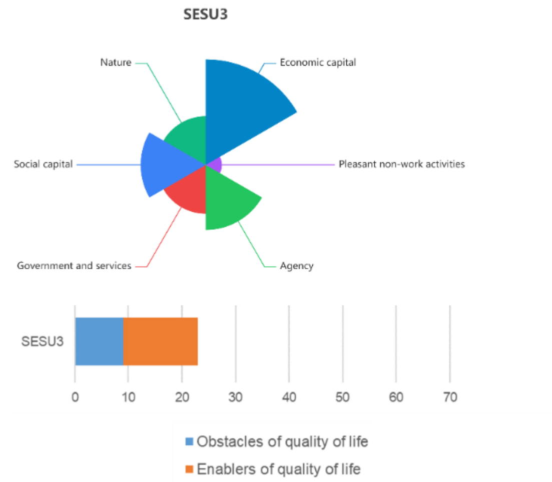
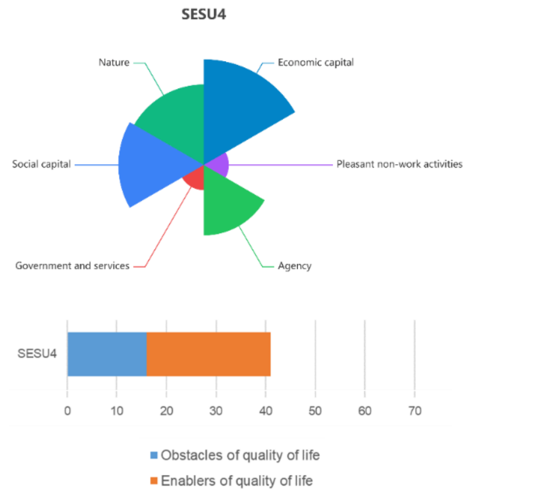


Figure 3. Current dimensions of Quality of Life (QoL) perceived across Social Ecological Units (SESU): 1. Social capital. 2. Nature. 3. Economic capital. 4. Pleasant non-work activities. 5. Agency. 6. Government and services. The SESU are shown in an increasing gradient of land transformation (SESU1, SESU2, SESU3, and SESU4), management intensity (SESU2, SESU3, SESU1, and SESU4), and individual governance (SESU1, SESU3, SESU2, and SESU4). Modified from Carvantes et al. press.

Table 3. Changes in the QoL dimensions across SESU. The length of the pie slice reflects the frequency of mentions of desirable QoL dimensions. Examples of the desirable QoL from the most frequent dimensions per SESU are presented to illustrate the concepts.

SESU	**Desirable QoL dimensions**	**Desirable QoL examples**
SESU1		**Economic capital**: "I would like another job, I tried with other jobs, and it did not work: a butcher shop that did not work." (he crossed the border/worked in the USA in an ice factory, he worked as an employee). "Working always helped me, but I want to change my profession, and no, I do not know how to do something else." **Nature:** "(...) to start an ecotourism project in ejido lands, interpretive trails, adventure tourism (...) we want to be the first in the region." **Agency:** "I am fine because I have holidays and can work on my land; I want to make the most of my time." **Enablers of quality of life**: "(...) health, being healthy allows me to work and have facilities."
SESU2		**Social capital:** "My family, to get better in life." **Economic capital:** "having money for buying more cows, asking for a loan (a credit to the bank). Now you have to provide capital before they give you money easier." **Agency:** I am fine; I work independently with what I have. I like this life." **Enablers of quality of life: "**Working hard, to make it better, to live in a better way (...) to have good nutrition, an income, to think in a job, if there is no job, there is no money" (increase livestock, the number of cows, pasture).
SESU3		**Economic capital:** "to have much money, that the government creates opportunities to trade" (which would help him to invest in expanding the paddock). **Agency:** "Happy, I have green land, my animals have food, which motivates me, makes me happy, I do not buy pasture, I drive myself as I can, not in which I want, little by little I am doing things as I want." **Social capital**: he feels peaceful, and his daughter supports him with medical appointments. **Enablers of quality of life**: "that nothing lacks in the house, not having an illness."

SESU4		**Economic capital:** he still has "things to do," and he aspires "to do more things" to get more material goods; from his view, he "never gets enough"; he always wants more projects. **Social capital:** he is kind to others, not to be aggressive with others, to be respectful towards people, to look after social relationships. **Nature**: to seek a way to make more pasture, get more benefits, and clean more paddock (enlarge it). **Agency**: to build "a small house to start a small business (in the town) and not coming to the paddock and working hard." **Enablers of quality of life**: economically speaking, he is happy; he has "an injured foot" and wants "to heal it."

Current Welfare Index and fulfillment of material and non-material needs

The highest levels of the Current Welfare Index were found in SESU4 (Fig. 4A), which is the unit with the highest land transformation and management intensity and a governance system that favors private land and individual management (Fig. 1). Yet, no significant differences in the Current Welfare Index were found among SESU (*F-statistic* = 1.192, df = 3, p-value = 0.337),

The perception of the fulfillment of non-material needs was highest in SESU1, with the lowest land transformation and lowest governance-driven individualism (Fig. 1 and Fig. 4B). Conversely, the unfulfillment of non-material needs was highest for SESU4 and SESU2 in comparison with SESU1 (*F-statistic* = 3.69, df = 3, p-value = 0.027). We found non-significant differences in the fulfillment of material needs among SESU (*F-statistic* = 1.178, df = 3, p-value = 0.34, Table S3).

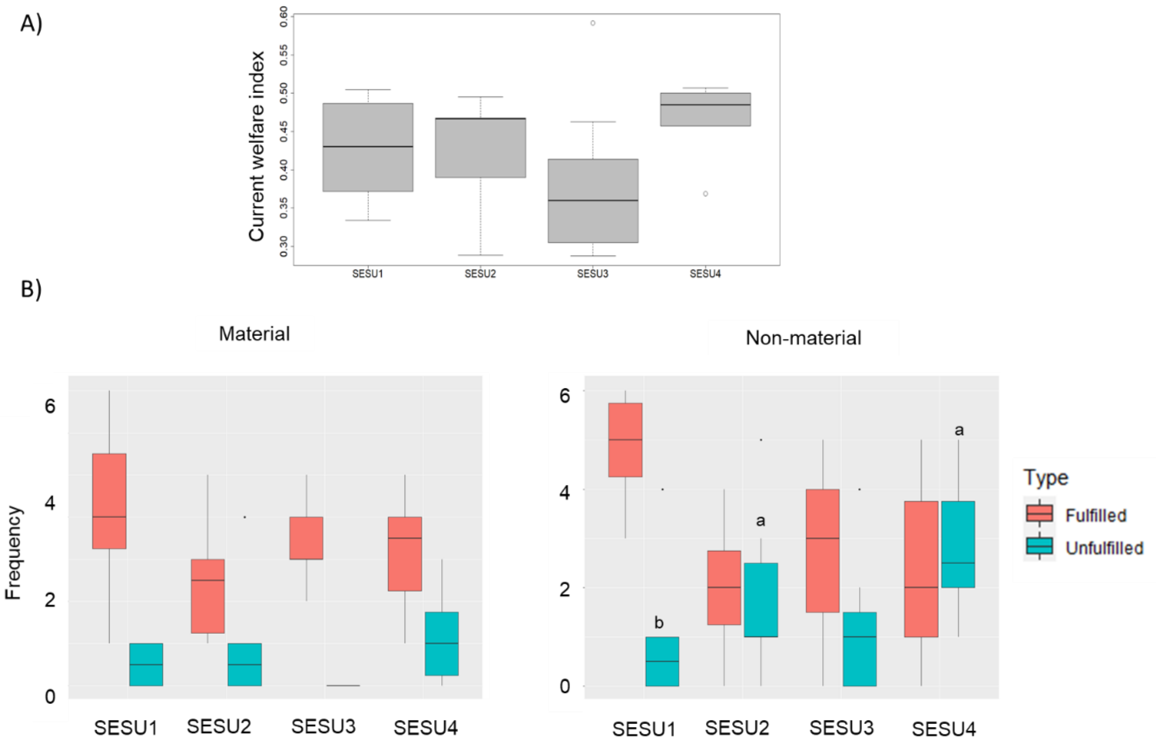


Figure 4. Changes in QoL among SESU: (A) Current welfare index differences among four SESU. (B) Material and non-material fulfillment or unfulfillment among four SESU. Different letters denote significant differences ($p < 0.05$). Lowercase letters indicate significant differences between SESU (Tukey posthoc test, p-value < 0.05).

Discussion

This study assessed the QoL of smallholders who inhabited a biodiversity hotspot area by combining subjective perceptions of QoL with objective indicators and explored how QoL differed across SES contexts. To our knowledge, this study represents the first exercise to evaluate how different QoL dimensions and material and non-material needs differ according to different levels of land transformation, management intensity, and governance practices. In the following, we discuss (1) how multiple QoL dimensions maintain a sense of good QoL by smallholders who inhabit a biodiversity hotspot and (2) the role of land transformation, management intensity, and governance in fulfilling a sense of good QoL. We end the discussion by reflecting on the limitations of this study.

A sense of a good QoL: an intricate of different dimensions and value-systems

Our results identified a wide variety of QoL dimensions (a total of six dimensions encompassing 48 different items) that describe the intimate relationship between smallholders' QoL and the nature they inhabit. Our results on the dimensions support former typologies of QoL, such as Tonon and Rodríguez de la Vega (2016), which highlights the value of material richness, work, and social relations, and Breslow et al. (2016), which points out self-determination as one key dimension. The three most relevant QoL items identified in this study were small community, economic prosperity, and access to jobs (Fig. 2). The social capital represented in the item of small community described the importance of family bonding and friends in sustaining relationships that nurture a life worth living. This dimension intrinsically connects with the notion of relational values (i.e., the importance ascribed to how ecosystems contribute to meaningful interactions between humans and nature and between humans concerning nature, Chan et al. 2016). This latter emphasizes the importance of human-human relations often mediated by nature (Chan et al. 2016). The second most important item -i.e., economic prosperity- described the importance of instrumental values (i.e., the importance of NCP/ES to people as a means to an end) when smallholders desire a good life. The relevance of instrumental values underpinning the desire for a good QoL has also been acknowledged in Northeast and Southern Thailand, where people regarded "money and assets" as the most important aspect of people's lives (McGregor et al. 2009). The third most important item –i.e., access to jobs- sometimes referred to the smallholders' satisfaction of having a meaningful occupation and other times to livelihood security and income. The first notion of 'job' as a source of QoL may connect again with relational values since it represents the importance of the farming job, while the second notion may refer to the instrumental value of farming as a means to gaining an income. The blending of instrumental and relational values underpinning the desire for a good QoL has been recently found in other farming contexts in Switzerland and Bolivia (Chapman and Deplazes-Zemp 2023, Ortiz-Przychodzka et al. 2023).

Our results also evidenced those perceived obstacles and enablers of QoL. The most important obstacle was related to the sense of decadence (13%) and negativity towards life, a feeling mostly held by older smallholders (Tauro et al. 2018). This sense of negativity towards life can also be explained by the difficult circumstances that peasants face daily in their rural life, such as being socially isolated or having fewer opportunities for career advancement (Davies 2008, Buciega et al. 2009). We found that good health, good food, tranquillity, and happiness were the most mentioned enablers. Those enablers can be associated with rural life (McGregor et al. 2009, Fagerholm et al. 2020). As previously mentioned, we argue that the enabler of good food may connect with the notion of instrumental values underpinning the importance of material means to achieve good QoL (i.e., good food). On the other hand, the relational values emphasizing the importance of human-human relations by sharing food and creating meaningful connections may lead to smallholder cooperation, happiness, and tranquillity to happen (Diener 1994).

Living well vs. Earning more: The role of land transformation, management intensity, and governance on QoL.

QoL experiences can reflect diverse visions of life. These visions are associated with collective strategies, planned actions, or how life is practiced in the territory (Tauro and Balvanera In press). We recognize the visions in the area are two-folded: on the one hand, the vision of the current farmer-rancher where "living well" prevails over a vision of "earning more."

The vision of "living well" is rooted in family and collective action (Bartra 2002, 2016). This vision is evidenced in SESU1, where governance practices mostly rely on commons (evidenced by the higher number of *ejidatarios*), and land transformation is the lowest. In this SESU, smallholders mentioned more frequently pleasant non-work activities as a dimension of QoL (Fig. 3). When the governance system is communal, it might favor a sense of community, where people who know their neighbors are more likely to engage in activities that foster mutual support and collective leisure activities (Arana and Wittek 2016). We hypothesize that the enhanced social capital facilitated by a communal governance system has led to the enjoyment of pleasant non-work activities by smallholders and a higher sense of a fulfilled life.

On the contrary, the vision of "earning more" follows the rationality of the accumulation where the smallholder aims to accumulate land through different mechanisms to extend the livestock practice (Torales-Ayala 2015, Hoelle 2018). This vision is illustrated in SESU4, where the governance practices rely on private land tenure, and smallholders expressed the highest ratio of unfulfilled material and non-material needs (Fig. 4b-c) while having the highest current welfare index score (Fig. 4a). Since SESU 4 presents the highest rates of land transformation and intensified management that has led to forest degradation and deforestation and whose smallholders have the highest welfare index, it perfectly exemplifies the environmentalist's paradox described by (Raudsepp-Hearne et al. 2010). At the same time, smallholders of SESU 4 presented the highest rates of perceived unfulfilled needs (Fig. 4 b) and were the ones who identified the highest number of obstacles to QoL (Fig. 3; Table 3). These results suggest that higher welfare levels do not align with perceptions of a fulfilled QoL and that they seek to increase their welfare further. For example, in SESU 4, many smallholders whose *ejidos* are all located along the coast intend to increase their income by engaging in economic opportunities emerging with beach tourism along the emerald coast (Riensche et al. 2019). For example, the quote, "*I would have liked to have more money to buy whatever I want, for instance, a car*" (S17, SESU4) illustrates the demand for more material goods. The desire for material needs can motivate progress and economic growth, but it can also lead to negative consequences, such as excessive materialism, unsustainable consumption patterns, or a perpetual cycle of seeking material fulfillment through external means (Eckersley 2006). In other words, *the more you have, the more you want.* Furthermore, this is tightly linked, most likely through feedback loops, with an increasing land cover transformation, land management intensity, and individualism fostered by private land tenure.

The sense of an unfulfilled QoL when having higher welfare, referred to as the happiness paradox (Easterlin et al. 2010), has been mostly reported in technological societies living in cities. By contrast, in rural contexts, people tend to place greater importance on the non-material dimensions of the QoL (e.g., Bartra 2002, Berry and Okulicz-Kozaryn 2009, Easterlin et al. 2011, Sørensen 2021). Our study, conducted in the rural setting of Chamela-Cuixmala, illustrates this dichotomy. On the one hand, smallholders of SESU4, who reported the lowest levels of fulfilled needs, have the highest level of welfare, promoted by deforestation, urbanization, and intensification of farming. On the other hand, smallholders of SESU1, who reported the highest levels of fulfilled needs, might be more connected with nature and care more for their animals than those in SESU4, as illustrated by the answer to the question 'What would you change to be better?': "*Leave the work and have a house on the hill and devote my life to cattle farming*." (S21, SESU1).

This dichotomy can be explained by the values underpinning the smallholders' desires for a good QoL. Smallholders in SESU4 hold mostly instrumental values and expressed arguments about the utility of nature for people, for example, illustrated by the quote, "*I still have many things to do, I have the ambition to have more things, in my opinion, I am never fulfilled, I always want more*" (S20, SESU4). This result might also suggest that when public policies foster values of prosperity and productivity, such as the TLC (for its Spanish acronym *Tratado de Libre Comercio* or NAFTA in English) and PROCEDE (Program for Certification of *Ejido* Rights and Titling of Urban Plots), they also promote desires of QoL that are associated with further fulfilling material (although non-basic) needs (Toledo 1996). By contrast, a community whose QoL is fulfilled, as in SESU1, might be more likely to hold other values than instrumental and value nature for other reasons. For example, the verbatim "*I really like livestock, that is where I live... the whole countryside seems beautiful to me*" (S11, SESU1) indicates that those relational values of caring for the animals, sense of place, and aesthetics contribute to a sense of fulfilled QoL. Yet, the downside might be that cattle ranchers in this region have tried to fulfill their material needs and lack opportunities by out-migrating to the USA or the states nearby (INEGI 2023), leading to family dismemberment.

Strengths and limitations of our approach

In this study, we combined both objective and subjective elements to explore the QoL. The in-depth interviews resulted in strong information for qualitative analysis; however, its small sample size may limit the statistical power of the analysis, so the quantitative results should be interpreted as exploratory rather than conclusive outcomes (Tauro et al. 2018). However, such effort represents an innovative approach in SES research, where few studies have combined empirically subjective and objective elements to unravel QoL (Smith and Clay 2010, Schueller and Seligman 2010). Because of this combination, we could identify that the SESU with the highest current welfare index score (SESU4) is not necessarily where smallholders express the highest level of fulfilled needs.

Furthermore, given that economic capital is a key dimension in all SESU, we could interpret that this dimension is not fully satisfied in either of the SESU. However, we could not set a minimum threshold for the current welfare index to interpret whether or not the material needs were fulfilled. Further analysis will benefit by having a minimum threshold for the current welfare index. The "threshold hypothesis," developed by (Max-Neef 1995), claims that every society experiences a period during which economic growth improves QoL, but only up to a certain point, the threshold point, after which, if there is further economic growth, QoL may start to decline. (Lawn 2003) has reviewed different welfare indexes and suggested that the threshold hypothesis is true for many of these indexes. In another example, (Armiento 2018) developed a sustainable welfare index and a threshold for Italy, confirming as well the threshold hypothesis. These examples prove that when working with welfare indexes, it is important to consider a threshold point.

Finally, the high relevance of the sense of decadence may also be related to the gender and age of the respondents, all men with an average of 60 years old. Men in rural areas are more vulnerable to experiencing extreme sadness due to the hegemonic masculinity in the rurality, which has served men well in good times, allowing them power and privilege, but unhealthy in times of significant stress (Narayan et al. 2002, Alston and Kent 2008) such as the constant droughts in the Chamela-Cuixmala region. In this study, we interviewed only those people making decisions on the land, all men; however, further research will benefit from considering other social factors, such as gender and age, in the analysis of QoL.

Conclusion

This paper arises from the initial motivation to understand how the different SES are associated with QoL. We have proved three main conclusions; first, land transformation, land management, and governance have different associations with QoL perceptions. Second, our study evidenced the two prevailing visions of QoL in different parts of a rural TDF landscape in Western Mexico. On the one hand, the vision of the current farmer-rancher where "living well" prevails, especially in areas with communal governance and medium management intensity, and on the other hand, the vision of "earning more" prevails in areas of individual governance and intensified land management. Finally, our study resulted in a rich set of 48 QoL items that advance the many existing typologies differentiating the QoL dimensions from the enablers and obstacles to QoL identified by the people in rural areas. With these results, we advanced in understanding the needs and satisfaction of Qol dimensions from people in the Global South and highlighting the diversity of viewpoints in rural areas. This information could represent important material for policymakers at all levels to foster visions that can motivate different conservation goals and sustainable uses of nature.

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Supplementary information Art3

Table S1. Quality of life dimensions, obstacles and enablers, and their frequencies in the Chamela-Cuixmala Region

Dimension	Subdimension	Frequency	Example
Social capital	Small community	39	“I love my children” “I am is happy” “I have my family”
	social interaction	22	“My daughter supports me with the visits to the doctor” “respect form others”, “speak to get along with people”, “[parties occur] at the expense of a group of people that cooperates”, “don’t get into what you don’t care about”
	Generations	15	“Children admire their parents”
	Cohesion	16	“They [his children] can collaborate with each other”, “his children call him to be pendant about him”, “I have a peaceable family”, “leave everything, at work in order to help my family”, “helping people who needs information”
	Traditions	9	“Respect from others”, “I have a peaceable family”, “children admire their parents”, “according to what you do, people will respect you”, “when there’s money, there’ll be a party”, “[you perform] the gift that God give you”, “people respect me”, “if your son likes livestock, he should work on it”
	Cultural heritage	4	“I appreciate beautiful things”
	Nurturing childhood	2	“I bought a house in Colima, where me and my sons live and afterwards his other daughters will arrive”, “giving advice to your children since they are little”
Economic capital	Work	43	“it’s fine, I have a job”, “it’s fine, I work in an independent way” “it’s fine, I have a job, an income”
	Economic prosperity (having economic capital)	41	“I want to make progress”, I bought a house”, “we [me and my family] have savings”, “these days I have been working and having good results”

	Work place	14	“When I go to the paddock I feel good, I work a little, I don’t make a big effort, but going to the paddock works as a distraction, and I am not staying all the day at home”, “I can work in my patch”, “I don’t want to sell my land and animals because it gives me illusion to having them”, “building a house in order to start a business (in the town) and not coming to the paddock and working hard”
	Job security	6	“I am tired, but fine because I have holidays and I can work on my land, I want to make the most out of my time”, it’s fine, I have a job, an income”, “we have to work hard, make it better, to live in a better way, having a good nutrition, an income, a job, if there’s no job, there’s no money, we need to increase livestock, the number of cows and pasture”
Agency	Freedom	28	“I am always doing something”, “I work independently, there’s no schedule”, “I take care of my own land”
	Ambition to have more	12	“Keeping the cows, but having more cattle", "I still have things to do, I aspire to do more things in order to get more material goods, from my view I never get enough, I always wants more projects [in relation to goods]", "I would like more of what I have, but I can’t, you can’t change your future”
	Motivation and intention to live	11	“I like this life”, “I want to take advantage of time to the maximum”, “with plans for a one-thousand years future”
	Mobility	12	“I can move freely”, “I walk all day”
	Sense of responsabilities	6	“Consuming what we produce”, “having responsibilities”, “free yourself from the duty to provide information about the *ejido*...disengage
Nature	Organisms (positive perspective)	15	“I feel happy and my animals have good food. That motivates me”

	Scenery	14	“Before I went to the plot by horse”, “with extra money he can hang out with his children (to the cinema, beach, football)”, “I see the landscapes”
	Observe nature	10	“I have green land”, “the vegetation”, “to sow”, “I like the hill [word for the Spanish *Monte,* in reference to the tropical dry forest”]
	Water	5	“[I would like that] rain doesn’t lack”, “[I would like that] it wouldn’t stop raining, to get future”, “Me and my family are healthy, as long as there is rain, water, work, if it misses the rain, there is no work”
	geographic features	3	“I am happy in the field, seeing the animals, the hill, I like the hill” [word for the Spanish *Monte,* in reference to the tropical dry forest”]
	Forests	2	“don’t cut down forests, keep some useless parts as paddock, it helps to vegetation, preserve *guayabillo* wood”, “to plant more trees and maintain them, to use forest in a sustainable way”
	Pleasant weather	2	“We cheer us up; we made a mistake coming here. Where we come from the weather is fine, occurs agriculture, we came of thinking the land was able for agriculture, at the beginning was tough, we became ranchers, I wanted to be farmer, [in our previous town] we had 8 ha, here they offered to us 35 ha per *ejidatario”*
	Closeness to nature	1	“I like livestock a lot, I live from it… all the field seems such a beautiful thing to me”
Pleasant non-work activities	Other outdoor activities	9	“going to the paddock serve me as a distraction… not being at home all day..., it makes me sleepy to be at home”
	Leisure	8	“I have work to do, with extra money I can hang out with his children (to the cinema, beach, football), to spend time with my family”, “I couldn’t answer well, life gives you some pleasant times and others… life offers everything”, “not having the need for working, living in a comfortable place, having fun”

	Tourism	3	"Start a ecotourism project in the *ejido* fields, interpretative trails, adventure tourism... we want to be the first in the region"
Government and services	Private services	6	"[having] a good mode of transport", having a good car"
	Accountable government	5	"in the public scenario, a change in the government, there is no future for the people below…", "that the government doesn't steal money from people", "in politics, to have a nice government"
	Public services (electricity, water, education)	5	"Medical appointments", "I am being attended for a doctor from Guadalajara", "before I went to the plot by horse, now I go by car"
	Public security	1	"In more than 10 years I am thinking about taking refuge with the daughters even if they live in a big town", "health and security"
Obstacles of quality of life	Sense of decadence	24	"I would like God give me life without getting old", "I am wasted, I can't work, I get tired quickly", "cruel because I lost my youth", "I didn't know how to take advantage of past opportunities", "I was wealthy and I spent it away", it is difficult to describe [a good life], I live in lack", "not come to the paddock to work sacrificially", "for people in their 50 or 60 years old there is no way to live fully anymore, there is no space for wishes", "at this age you can't aspire to have something, a person can't work, or keep what you have"
	self-awareness and limit awareness	18	"To be aware about what you do wrong", "life depends on external forces", "we have to deal with life as it comes"

	Bad quality of life	11	"insecurity generates me worries", everything is suffering", "withered, without hopes", "I doesn't feel safe [in life]", "wasted, I worked hard", "it's only working", "I would have liked that God gave me life without getting old", "I can't thing or imagine the good life", "due to my age I can't work anymore, but I don't want to receive alms"
	Bad health	9	"Exhausted, tired", "old man, everything is suffering", "I would have liked that God gave me life without getting old"
	Sense of scarcity	7	"I was wealthy and I spent it away", "what does oneself? pure work", "sacrifice"
	Sense of concern	4	"life is a function of external forces, I feel disappointed, insecurity generates me concern. something is not working well, but you don't have to make your life miserable for that", "I depend on family, at this age there is no job, if your family supports you… if they make you part of your own family, if they don't, the alternative is to ask for charity"
	Public insecurity	4	"Here, I enjoy my life, but I am dissatisfied because of the insecurity", "what can I ask for? To eat and live peaceful, if they allow us. Our current situation [insecurity] is the problem, bosses can't control that", "we don't know what our destiny is [in terms of insecurity]"
	Organisms (negative perspective)	2	Sometimes I deny to take care of my animals, but what do I do? Pure work", "to build a little house in order to start a business (in the village) and not going to the paddock and work hard"
	Sadness	2	"What would I do...? to look up for a good life doesn't fit with me, it's tough to describe it, I have a life of misery", "I don't feel happy"

Enablers of quality of life	Good health	19	“To be less tired”, “I am very good, fulfilled, I have a complete family, I am happy with my family, I work independently, without an schedule, I am healthy and strong”, “thank God, the world owes me nothing, I asked to God that my family doesn’t get sick and he gave it to me [in the sense of drug addict children]”
	Good food (for human and animals)	18	“I don’t buy grass”, “we enjoy what we eat”
	Tranquillity	18	“To feel fine”, “little by little you make progress”, the world owes me nothing”, “I am fulfilled”
	Happiness	16	“I am not upset for being in the world”, “I feel fine”, “I love my children”
	Good quality of life	10	“The benefits level have raised”, “I am fulfilled”, “If I could, I would move forward”, “I am satisfied”, “being healthy allows me to work and have facilities”, “to be clean”
	Sense of plenitude	10	“Really fine, completed” “fulfilled”, “yes [I am very satisfied with my life] because I have reached this period in my life”
	Housing	6	“To have the necessary: such as a car, which I can go to the city with. A nice house, with services, well painted and finished”, “that nothing is missing in the house, not having illness", "getting off from work, have a house on the hill (on your plot), to dedicate yourself to cattle"
	Sense of place	5	“I enjoy staying in the village”, “he feels fine with all people”

Table S2. Data set with the information of the smallholders

Smallholder	SESU	Education	Material Fulfilled	Material Unfulfilled	non-material Fulfilled	non-material Unfulfilled	Age	Years living in the zone
S1	SESU3	primaria	3	1	4	4	72	30
S2	SESU3	primaria	1	1	4	1	34	34
S3	SESU4	sin escuela	3	0	4	1	77	40
S4	SESU2	sin escuela	5	3	1	5	79	60
S5	SESU3	primaria	1	0	6	0	63	38
S6	SESU2	primaria	7	0	5	4	50	41
S7	SESU2	primaria	4	0	0	2	54	50
S8	SESU3	secundaria	1	0	1	1	55	38
S9	SESU2	primaria	5	0	2	3	40	40
S10	SESU1	secundaria	4	0	5	0	54	46
S11	SESU1	primaria	2	0	2	0	53	48
S12	SESU4	sin escuela	3	1	3	0	77	60
S13	SESU2	primaria	3	0	0	4	74	25
S14	SESU1	primaria	5	0	3	2	67	66
S15	SESU4	preparatoria	4	1	4	1	40	40
S16	SESU1	preparatoria	3	0	1	0	69	48
S17	SESU4	sin escuela	2	0	2	0	73	44
S18	SESU2	secundaria	3	0	3	1	50	45
S19	SESU3	sin escuela	4	0	4	1	59	35
S20	SESU4	primaria	1	4	1	5	76	15
S21	SESU1	primaria	3	1	0	1	59	45
S22	SESU4	primaria	6	0	6	1	44	44
S23	SESU1	secundaria	2	2	3	2	62	33
S24	SESU3	sin escuela	4	1	5	0	70	70
S25	SESU3	primaria	4	1	5	3	60	53

Table S2. Continuation Data set with the information of the smallholders

Smallholder	SESU	CWB index	Diversity of income sources	Number of landrights	Number of owned plots	Number of cattle	Number of federal programs support that they receive	Assistance to the doctor in the last year	Facility of access to water	Reception of remittances?
S1	SESU3	0.48011364	1	2	1	100	1	1	Hard	yes
S2	SESU3	0.28844697	2	1	1	15	0	1	Medium	no
S3	SESU4	0.36003788	1	1	4	30	2	1	Hard	no
S4	SESU2	0.49011364	1	1	1	24	0	0	Easy	yes
S5	SESU3	0.33410953	1	1	2	4	1	2	Medium	no
S6	SESU2	0.45511364	3	1	1	40	1	1	Easy	no
S7	SESU2	0.50662878	3	1	7	100	1	2	Easy	no
S8	SESU3	0.45719697	2	1	1	20	0	0	Medium	yes
S9	SESU2	0.39015152	2	1	5	50	0	0	Medium	no
S10	SESU1	0.36492424	1	1	3	19	1	2	Easy	no
S11	SESU1	0.59128788	4	2	4	60	1	1	Easy	no
S12	SESU4	0.37155755	1	1	1	40	1	1	Easy	no
S13	SESU2	0.46231061	1	1	2	230	2	0	Hard	no
S14	SESU1	0.28731061	2	1	2	35	1	3	Medium	no
S15	SESU4	0.50481061	2	1	2	57	2	1	Easy	no
S16	SESU1	0.31962121	2	1	4	58	0	3	Easy	no
S17	SESU4	0.46761364	1	1	1	120	1	3	Easy	yes
S18	SESU2	0.49507575	2	1	8	120	1	2	Easy	no
S19	SESU3	0.29034091	1	1	3	40	1	1	Hard	no
S20	SESU4	0.46761364	1	1	1	70	1	1	Medium	yes
S21	SESU1	0.46534091	2	1	3	35	1	2	Medium	yes
S22	SESU4	0.40511363	3	1	1	20	1	2	Easy	no
S23	SESU1	0.5	2	1	11	300	1	3	Medium	no
S24	SESU3	0.48680902	1	1	2	30	2	0	Medium	no
S25	SESU3	0.36837122	3	1	4	50	1	1	Hard	no

Table S3. Differences between material fulfilled-unfulfilled per SESU

Material	**p**	**F-value/X^2**	**Df**
Fulfilled	0.342	F= 1.178	3
Unfulfilled	0.081	X^2=6.72	3
Non-material			
Fulfilled	0.027*	F=3.69	3
Unfulfilled	0.11	X^2= 5.97	3

Tukey HSD Non-material, fulfilled

SESU1-SESU2 p= 0.03; SESU1-SESU4 p= 0.05

Table S4. Differences per current QoL dimensions and obstacles and enablers per SESU

	p	**F-value/X^2**	**Df**
Economic capital	0.147	F= 1.98	3
Social capital	0.978	X^2=0.195	3
Agency	0.938	X^2=0.41	3
Nature	0.82	X^2=0.92	3
Pleasant non-work activities	0.125	X^2=5.72	3
Government and services	0.326	X^2=3.457	3
Obstacles of QoL	0.209	X^2=4.53	3
Enablers of QoL	0.687	X^2=1.47	3

Table S5. Differences per desirable QoL dimensions and obstacles and enablers per SESU

	p	**F-value/X^2**	**Df**
Economic capital	0.57	X^2=2.002	3
Social capital	0.524	X^2=2.239	3
Agency	0.713	X^2=1.367	3
Nature	0.296	X^2=3.692	3
Pleasant non-work activities	0.27	X^2=3.885	3
Government and services	0.709	X^2=1.385	3
Obstacles of QoL	0.413	X^2=2.86	3
Enablers of QoL	0.1	F= 2.365	3

Table S6. T-test/ Mann Whitney between current and desire QoL

SESU1	**p**	**W/T**	**Df**
Economic capital	0.241	T= 1.245	10
Social capital	0.08	29	
Agency	0.562	22	
Nature	0.731	20.5	
Pleasant non-work activities	0.44	23	
Government and services	0.246	25	
Obstacles of QoL	0.6	21	
Enablers of QoL	0.002	T=3.97	10
SESU2	**p**	**W**	**Df**
Economic capital	0.45	T=0.785	10
Social capital	0.366	24	
Agency	0.067	29.5	
Nature	0.234	T=1.264	10
Pleasant non-work activities	1	18	
Government and services	1	18	
Obstacles of QoL	0.446	23	
Enablers of QoL	0.325	24.5	
SESU3	**p**	**W**	**Df**
Economic capital	0.189	T=1.391	12
Social capital	0.077	38.5	
Agency	0.07	38	
Nature	0.18	34	
Pleasant non-work activities	1	24.5	
Government and services	0.783	27	
Obstacles of QoL	0.411	31	
Enablers of QoL	0.002*	T=3.739	12
SESU4	**p**	**W**	**Df**
Economic capital	0.139	T=1.604	10
Social capital	0.623	21.5	
Agency	0.587	T=0.561	10
Nature	0.822	T=0.23	10
Pleasant non-work activities	0.929	19	
Government and services	0.787	20	
Obstacles of QoL	0.181	T=1.435	10
Enablers of QoL	0.885	T=0.147	10