INSTITUTO POTOSINO DE INVESTIGACIÓN CIENTÍFICA Y TECNOLÓGICA, A.C.

DIVISIÓN DE CIENCIAS AMBIENTALES

Social-ecological participatory observatory sites in arid northern Mexico: co-definition of shared space and future challenges of drought under climate change

Tesis que presenta

Gerardo Esquivel Arriaga

Para obtener el grado de

Doctor en Ciencias Ambientales

Co-directora: Dra. Elisabeth Huber-Sannwald

Co-director: Dr. Víctor Manuel Reyes Gómez

Asesor: Dra. Natalia Martínez Tagüeña

Asesor: Dr. Luis Carlos Bravo Peña

Asesor: Dr. Juan Alberto Velázquez Zapata

San Luis Potosí, S.L.P., 22 de abril de 2025

Constancia de aprobación de la tesis

La tesis "**Social-ecological participatory observatory sites in arid northern Mexico: co-definition of shared space and future challenges of drought under climate change**" presentada para obtener el Grado de Doctor en Ciencias Ambientales fue elaborada por **Gerardo Esquivel Arriaga** y aprobada el 22 **de abril de 2025** por los suscritos, designados por el Colegio de Profesores de la División de Ciencias Ambientales del Instituto Potosino de Investigación Científica y Tecnológica, A.C.

Dra. Elisabeth Huber-Sannwald
Codirectora de la tesis

Dr. Víctor Manuel Reyes Gómez
Codirector de la tesis

Dra. Natalia Martínez Tagüeña
Miembro del Comité Tutoral

Dr. Luis Carlos Bravo Peña
Miembro del Comité Tutoral

Dr. Juan Alberto Velázquez Zapata
Miembro del Comité Tutoral

Créditos Institucionales

Esta tesis fue elaborada en la División de Ciencias Ambientales del Instituto Potosino de Investigación Científica y Tecnológica, A.C., bajo la codirección de la Dra. Elisabeth Huber-Sannwald y el Dr. Víctor Manuel Reyes Gómez.

Durante la realización del trabajo el autor recibió una beca académica del Consejo Nacional de Ciencia y Tecnología (293155) y del Instituto Potosino de Investigación Científica y Tecnológica, A. C.

El presente trabajo fue realizado gracias al apoyo del Consejo Nacional de Humanidades, Ciencia y Tecnología, a través del proyecto de investigación PRONAII 319059 denominado "OBSERVATORIOS PARTICIPATIVOS SOCIO-ECOLÓGICOS (OPSE) DE ZONAS ÁRIDAS. ETAPA II: CO-DEFINICIÓN Y CO-GENERACIÓN DEL CONOCIMIENTO PARA LA DIVERSIDAD CULTURAL Y BIÓTICA Y EL DESARROLLO SOSTENIBLE", coordinado por la Dra. Elisabeth Huber-Sannwald como Responsable Técnico.

ACTA DE EXAMEN

Dedicatorias

A mi familia

Mis padres Mauro y Ma. Isabel

Mis hermanos Oscar y Eleazar

Mis hijos Gerardo y Nicole

Agradecimientos

A la Secretaría de Ciencia, Humanidades, Tecnología e Innovación (Secihti) y al Instituto Potosino de Investigación Cientifica y Tecnológica (IPICYT) por el apoyo financiero y las facilidades para llevar a cabo los estudios de posgrado.

Un sincero y amplio agradecimiento a la Dra. Elisabeth Huber-Sannwald por la oportunidad de colaborar en su grupo y proyecto de investigación que permitió realizar el presente trabajo de inestigación.

Un extenso agradecimiento a mi comité asesor, la Dra. Elisabeth Huber-Sannwald, Dr. Víctor M. Reyes Gómez, Dra. Natalia Martínez Tagüeña, Dr. Luis Carlos Bravo Peña y al Dr. Juan Alberto Velásquez Zapata por la paciencia, dedicación, apoyo, disposición, aportaciones y comentarios desde el punto de vista académico como personal, que inculcan importantes contribuciones para mi desarrollo profesional y personal.

A las personas que directa o indirectamente contribuyeron con la aportación de información, conocimientos y experiencias, especialmente de la Reserva de la Biosfera de Mapimí, que permitieron generar información novedosa para el desarrollo de esta tesis de investigación.

A mis compañeros doctorantes y pos-doctorantes que me brindaron apoyo durante el proceso de investigación.

Index

List of Tables

List of Figures

Appendix

Resumen

Las zonas áridas son los sistemas socioecológicos más extensos, diversos y a la vez altamente vulnerables al calentamiento global de nuestro planeta. Los patrones de aridez y sequía causan una creciente presión sobre los recursos de la tierra y el agua y son algunos de los mayores problemas globales y locales de cambio ambiental y social, por lo que constituyen un reto para la ciencia y la sociedad. Las zonas áridas cubren aproximadamente el 65% del territorio mexicano, donde habita más del 60% de la población total. Recientes consensos científicos sugieren que las posibles soluciones a la degradación de la tierra deben ser identificadas e implementadas en el contexto de las condiciones ambientales, sociales, económicas y políticas locales. Al mismo tiempo, la complejidad del riesgo de sequía exige políticas intersectoriales que tengan en cuenta la diversidad regional, aprovechen los conocimientos locales y promuevan la participación de las comunidades. En esta investigación, nuestros sitios de estudio, los Observatorios Participativos Socioecológicos (OPSEs) se encuentran a lo largo de un transecto oeste-este en las tierras secas del norte de México. Los OPSEs son una innovación socio-ambiental y proporcionan un espacio para la consolidación de alianzas formales e informales para la sostenibilidad a través de comunidades de aprendizaje que comparten diversos conocimientos, tecnologías e innovaciones. Como resultado de una encuesta entre los diferentes sectores que integran los OPSEs se definieron los temas prioritarios mas importantes entre los cuales destacan: cambio climático, sequía, y escasez de agua. En esta investigación, el objetivo general fue analizar el valor socio-ambiental vinculado a la tierra compartida por múltiples partes interesadas como base para co-definir los límites espaciales de los sistemas socio-ecológicos, y analizar los cambios futuros de la precipitación y la posible ocurrencia de sequías bajo condiciones de cambio climático en el contexto de la red de OPSEs, en tres capítulos principales. El capitulo uno demostró que la valoración de la tierra por múltiples actores en el OPSE Mapimí a través del mapeo de lugares significativos puede ser integrada para generar variables socioeconómicas que no están disponibles en formato vectorial y combinadas con variables biofísicas permitió la delineación espacial de un sistema socio-ecológico y la estimación de unidades socio-ecológicas. Esta delimitación es dinámica y flexible, sujeta a actualización y reevaluación, porque se basa en la percepción, la intuición, la experiencia, el interés, el conocimiento y el juicio de diferentes grupos de partes interesadas altamente experimentadas y conocedoras de las condiciones medioambientales locales y actuales. El capitulo dos resalta que, para una adecuada caracterización de las condiciones de sequía, es indispensable contar con datos de precipitación de buena calidad. Este capitulo examinó cómo la red de pluviómetros en las zonas áridas de México, que está distribuida de manera muy heterogénea y frecuentemente con conjuntos de datos incompletos, puede

compensarse con información derivada de conjuntos de datos de precipitación global. Con base en el desempeño de cinco conjuntos de datos globales de precipitación, sugerimos utilizar los datos climáticos CHIRPS y AgERA5 para llenar los vacíos de información de las estaciones pluviómetros existentes. El capitulo tres examinó la ocurrencia (frecuencia, severidad y duración) de sequías meteorológicas históricas (1981-2010) y futuras (2041-2100) a escala temporal de 12 meses sobre la red OPSE utilizando el Índice Estandarizado de Precipitación (SPI). Asimismo, se analizó la percepción del concepto de sequía y las medidas de adaptación en el OPSE Mapimí. Los resultados sugieren que en el futuro cercano (2041-2070) y lejano (2071-2100), se proyecta un incremento de la precipitación media anual para la red OPSEs. En general, las condiciones de sequía en la escala de tiempo de 12 meses en el futuro cercano y lejano, presentaron eventos menos frecuentes con una disminución en su duración. En el OPSE Mapimí, la percepción del concepto de sequía se encontró mayoritariamente vinculada a cuestiones relacionadas con las precipitaciones (ausencia de lluvias) y la vegetación (ausencia de pastos). Los años 1951, 1953, 1970, 1972, 1977, 1978, 1984, 1986, 1988, 1989, 1990, 1995, 1997, 1998, 2001, 2002, 2008, 2011, 2012 y 2019 como los eventos de sequía más relevantes ya que afectaron sus condiciones de vida. Los años 1958, 1987, 1990 y 2010 fueron identificados como los más lluviosos, provocando inundaciones en el ejido Laguna de Palomas.En el OPSE Mapimi, las comunidades locales reconocieron cambios en el clima (más calor y menos lluvia), aunque no los expresaron como «cambio climático». Las medidas de adaptación para enfrentar la sequía por parte de los ganaderos consisten en vender algunos animales para mantener a los restantes o cortar y quemar nopal como fuente de alimento para el ganado. Los productores de sal y los ecoturistas tienen empleos temporales o reciben apoyo económico de familiares. Una de las innovaciones de esta investigación es que el proceso promueve un intercambio de información (científica y no científica) y se aborda desde dos perspectivas diferentes: una basada en la observación y la medición (por ejemplo, morfometría del relieve, uso/cubierta del suelo, etc.) y otra fenomenológica, basada principalmente en las experiencias de las personas (cartografía de lugares significativos a partir de las percepciones/valoraciones del espacio por parte de múltiples sectores y la percepción del concepto de sequía), por lo que esta investigación representa un enfoque transferible y replicable. El modelo OPSEs, en un tiempo de 4-5 años (a definir), se observa que ya tienen importantes implicaciones para futuras investigaciones interdisciplinarias que podrían centrarse en la gobernanza ambiental con un enfoque muy importante en la gobernanza del agua, la modelación climática, la resiliencia comunitaria y preguntas novedosas que conduzcan a desarrollar enfoques más sostenibles para la gestión de las tierras secas de México.

Palabras clave: Sistemas Socio-ecologicos, sequía, cambio climático, conocimiento local, desarrollo sostenible

Abstract

Drylands social-ecological systems are one of the most extensive, diverse, yet highly vulnerable social–ecological systems of our planet Earth. Aridity and drought patterns cause increasing pressure on land and water resources and are some of the largest global and local environmental and social change problems and thus are a challenge for science and society. Drylands cover approximately 65% of the Mexican territory; over 60% of the total population inhabit these areas. Recent scientific consensus suggests that to potential solutions to land degradation need to be identified and implemented within the context of local environmental, social, economic and political conditions. At the same time, the complexity of drought risk demands cross-sectoral policies accounting for regional diversity, leveraging local knowledge and promoting communities' engagement. In this research, our study sites, the Social-ecological participatory observatories (OPSEs) lie along a west–east transect in northern Mexico drylands. The OPSEs are a social-ecological innovation and provide a space for the consolidation of formal and informal alliances for sustainability through learning communities that share diverse knowledge, technologies, and innovations. As a result of a survey applied to actors of various sectors linked to the OPSEs, priority issues were defined, including climate change, drought, and water scarcity. In this research, the general objective was to analyze the social-environmental value linked to shared land by multiple stakeholders as a basis to co-define the spatial boundaries of social-ecological systems and analyze potential future changes in precipitation and the potential occurrence of droughts under climate change conditions in the context of the OPSE network divided in three chapters. Chapter one showed that the valuation of land by multiple stakeholders by identifying and mapping different meaningful places in the OPSE Mapimí can be integrated to generate socio-economic variables that are not available in vectorial format and combined with biophysical variables allowed the spatial delineation of a Social-ecological system and the estimation of social-ecological units within the OPSE Mapimí. This delineation is dynamic and flexible and subject to updates and re-evaluations, as it is based on the perception, intuition, experience, interest, knowledge and judgment of different stakeholder groups, which are highly experienced and knowledgeable about the local and current social-environmental conditions. Chapter 2 highlights that for an adequate characterization of drought conditions, good quality precipitation data are indispensable. This chapter examined how the rainfall gauge network in Mexico's drylands that is highly heterogeneously distributed and frequently with incomplete datasets, can be compensated by information derived from global precipitation datasets. Based on the performance of five global precipitation datasets, we suggest using CHIRPS and AgERA5 climatic data to fill gaps of observational rain gauge information. Chapter 3 examined the occurrence (frequency, severity and duration) of historical (1981-2010) and future (2041-2100) meteorological droughts at time scale of 12 months for the OPSEs network using the Standardized Precipitation Index (SPI). Likewise, the perception of the concept of drought and adaptation measures were analyzed in the OPSE Mapimí. Results suggest that in the near (2041-2070) and far (2071-2100) future, an increase in the average annual precipitation is projected for the OPSE network. In general, drought conditions at the 12-months time scale for the near future, presented less frequent events with a decrease in its duration. In the OPSE Mapimí, the drought concept mostly found to be linked with issues related to rainfall (no rain) and vegetation (no forage). The years 1951, 1953, 1970, 1972, 1977, 1978, 1984, 1986, 1988, 1989, 1990, 1995, 1997, 1998, 2001, 2002, 2008, 2011, 2012 and 2019 were identified as the most important drought events since they affected their living conditions. The years 1958, 1987, 1990 and 2010 were identified as the wettest years, causing flooding in the ejido Laguna de Palomas. Changes in the weather were generally recognized by the respondents (more heat and less rain), if not expressed as "climate change". Adaptation measures to face drought in case of cattle raising include selling some animals to maintain the remaining animals or cutting and burning prickly pear as an alternative food source for livestock. The salt producers and ecotourism people were temporarily employed or received economic support from relatives. One of the innovations of this research is that the process promotes an exchange of information (scientific and non-scientific) and is approached from two different perspectives: one based on observation and measurement (e.g., relief morphometry, land use/cover, etc.) and a phenomenological one, based mainly on people's experiences (mapping of significant places from valuations of space by multiple sectors and the deep understanding of the concept drought. Hence, this research represents a transferable and replicable approach. The OPSE model, in a time frame of 4-5 years (to be defined), is observed to have important implications for future transdisciplinary research that could focus on collaborative social-environmental governance with the important focus on water governance, climate modeling, community resilience and novel questions that could lead to the development of more sustainable approaches for the adaptive and integral management of Mexico's drylands.

Key words: Social-ecological systems, drought, climate change, local knowledge, sustainable development.

Chapter 1

1. Introduction

Human activities have been changing the ecosystems upon which humanity depends on in unprecedented and profound ways for several decades (Steffen et al. 2004, 2007; Rockström et al., 2009, 2024). Navigating the environmental and societal changes that mark the new geological era of the Anthropocene (Steffen et al., 2011) pose major challenges to researchers, policy makers, and civil society organizations. They are becoming increasingly dependent on transdisciplinary and participatory research and practice-orientated approaches that render an in-depth understanding of the complex nature and implications of the dynamic interactions that link ecosystems and human societies at all scales (Folke et al., 2016).

A social-ecological system's (SES) perspective is an emerging approach to understand the intertwined and interdependent relationships between society and nature (Biggs et al., 2021). The concept of SES builds on the notion that 'the delineation between social and natural systems is artificial and arbitrary' (Berkes and Folke, 1998) emphasizing that people and nature are intrinsically intereconnected. Nature no longer merely sets the space in which social interactions take place; likewise, people and societies are not just an external driver in ecosystem dynamics (Folke et al., 2011). Social-ecological systems are not merely social plus ecological systems, but cohesive, integrated systems characterized by strong connections and feedbacks within and between social and ecological components that determine their overall dynamics (Folke et al., 2010).

The concept has helped facilitate increased recognition of the complexity and coupledness of human and natural systems (Liu et al., 2007), has improved collaboration across disciplines and between science and society (Carpenter et al., 2012), has increased methodological pluralism and acknowledged the importance of different knowledge systems that has led to improved system's understanding (Tengö et al., 2014), and has manifested in and shaped major global policy frameworks and initiatives, such as Future Earth (Rockström, 2016), the United Nationes 2030 Agenda for Sustainable Development (WBG, 2015; UN 2015).

1.1 Drylands social-ecological systems are complex systems

Drylands are characterized by climate variability and water scarcity because of the low rainfall and high evapotranspiration rate from surface (Safriel et al., 2005). Drylands are broadly defined as land areas where the ratio of mean annual precipitation to mean annual potential evapotranspiration (i.e. aridity index) is less than 0.65 (Middleton and Thomas, 1997). According to this definition, drylands cover about 46.2% (±0.8%) of Earth's land surface and are inhabited by nearly 2.6 billion people (39 % of world population) and despite being water-limited areas, over 43% of the global cropland area is located in drylands (Cherlet et al., 2018; Koutrolis, 2019; IPCC, 2019).

In this millennium, drylands will expand by 23% and 11% relative to the observed baseline (1961-1990) by the end of century and will respectively cover a total of 56% and 50% of the global land surface under RCP8.5 and RCP4.5 (Huang et al., 2016). Additionally, Koppa et al. (2024) found that the warm, dry air flowing over drylands contributes to downwind dryland expansion and can cause the aridification of those areas. They found that more than 40% of the observed increase in aridity over regions that became drylands from 1981 to 2018 was due to self-expansion.

In addition to the immediate provision of food, drylands provide a broader set of ecosystem services (Stafford-Smith et al., 2009). The ecosystems of drylands are quite vulnerable and sensitive to external influences, for example, human activities and climate variabilities (IPCC, 2019). In dryland regions, human inhabitants draw upon local ecosystems to extract diverse resources, ranging from water to food, all in service of enhancing human well-being. The management of these ecosystems is profoundly influenced by an array of factors, including governmental policies, subsidies, payments for ecosystem services, and local to global markets (Fu et al., 2024).

These social processes hold pivotal significance, shaping the very fabric of SESs in drylands—encompassing their structure, attributes, and intricate interactions (Maestre et al., 2016). While the ramifications of climate change reverberate globally, adaptive strategies predominantly manifest at the local or regional level, necessitating the holistic consideration of ecological, social, and economic stimulants and responses inherent to specific SESs, particularly within dryland contexts (Scheffer et al., 2015). Given the biotic and cultural diversity of global drylands and changes in the relationships between SES components, more coordinated research and development models need to be designed and tested to assist multi-stakeholder partnerships for sustainable development (Higham et al., 2024) and for changing dryland SESs (Fu et al., 2024).

Due to the increased human demand (food mainly) and climate change, dryland ecosystems are facing severe problems (Cherlet et al., 2018). Degradation of drylands will lead to the loss of biodiversity (de Albuquerque et al., 2024), damage to ecological integrity (Bernardino et al., 2025) and threat to food security (Stavi et al., 2022). It is estimated around 10%-20% of drylands have already degraded and new degradation is still happening every year (Yirdaw et al., 2017) both as a consequence of land use and climate change (Huang et al. 2020). Burrell et al (2020) found that between 1982 and 2015, 6% of the world's drylands underwent desertification driven by unsustainable land use practices compounded by anthropogenic climate change.

The global drying trend is expected to continue throughout this century (Huang et al., 2016). Feng and Fu (2013) indicated that the increase can reach up to 10% compared to the period 1961–1990, while Koutroulis (2019) stated that drylands could increase by up to 7%. Notwithstanding, a recent study, found that drylands are noticeably recovering, with the total area of improved drylands being 1.4 times that of degraded. The degradation degree is primarily slight, while improvement is significant. The combined effects of climate change and human activities dominate the processes of land degradation accounting the 82.67% (Yan et al., 2024).

Climate change exacerbates negative impacts on vegetation diversity and cover (Mirzabaev et al., 2022), while disruptions in species interaction networks caused by inadequate management practices compromise the landscape resilience of dryland SESs in the face of extreme events (Hoover et al., 2014). Modeling work shows that some world regions will experience higher temperature increase than others, and that some regions will receive more rainfall while others will experience more frequent extreme events, like droughts (Costello et al., 2022) or suffer from severe aridity (Vicente-Serrano et al., 2024).

In this context, the extended droughts and increased variability in precipitation directly exacerbate socio-environmental degradation in drylands (Stott, 2016, Huang et al., 2020). Given the speed and intensity of climate change and socio-economic development, which are likely to exacerbate problems such as land degradation, poverty, and food and water insecurity, systematic research on the socio-ecological interaction of such processes in dryland SESs is essential. In order to move towards sustainable SESs, this research must be conducted at multiple scales and with multiple stakeholders to capture synergies between Sustainable Development Goals and manage conflicts that may arise due to trade-offs between goals (Fu et al., 2024).

1.2 The International Network for Drylands Sustainability

The International Network for Drylands Sustainability (RISZA by its Spanish acronym) was launched in Mexico (www.risza.com.mx) in 2017. The objective of RISZA is to co-generate and foster research, development, and innovation at the national level with a strong regional and inter-sectoral emphasis. RISZA aims to guide and facilitate transdisciplinary and participatory research including multiple stakeholders to foster the collective production of useful knowledge (Huber-Sannwald et al., 2020) and pursue the advancement of the science of sustainability, public policy advocacy and sustainable development in northern Mexico drylands (Lauterio et al., 2021).

To achieve sustainable development objectives in drylands, the integration of diverse knowledge systems (local to general, informal to formal, novice to expert, tangible to implicit and explicit, traditional and local to scientific and universal) is required (Raymond et al., 2010, Tengö et al. 2017). The development of transdisciplinary (Brandt et al., 2013) and participatory research (Cornwall and Jewkes, 1995) is based on the continuous generation of knowledge and dialogue (Merçon, 2022) to efficiently create sustainable local development proposals with the full participation of local stakeholders. Collaborations between multi-stakeholders at all levels, are fundamental for the co-production of useful knowledge (Clark et al. 2016) for the evaluation and decision making related to the sustainable use and management of drylands SES.

1.3. The Social-ecological Participatory Observatories in northern Mexico drylands

RISZA addresses the grand challenges emerging in drylands with a transdisciplinary focus, to protect the biotic and cultural diversity as an essential foundation for sustainable development. One of RISZA's modus operandi are the Social-Ecological Participatory Observatories (OPSE, Spanish Acronym for Observatorios Participativos Socio-Ecológicos), understood as living laboratories in real territories, where pathways of action are explored with participatory methodologies. The OPSE approach is a social-ecological innovation to co-produce, share, exchange and store knowledge to jointly develop local action plans and which facilitate decision making in the context of SES. In this sense, the OPSE are face-to-face and virtual sites/spaces, where new knowledge is collected, exchanged and co-generated as an innovation hub for sustainable development in drylands (Lauterio et al., 2021).

This research considers a network of dryland systems associated with local OPSE along a west–east transect reaching from the Mediterranean climate in northwest (NW) Mexico, coastal arid climate in the Sonora Desert, and semiarid climate in the Chihuahua Desert in central and east Mexico (Figure 1).

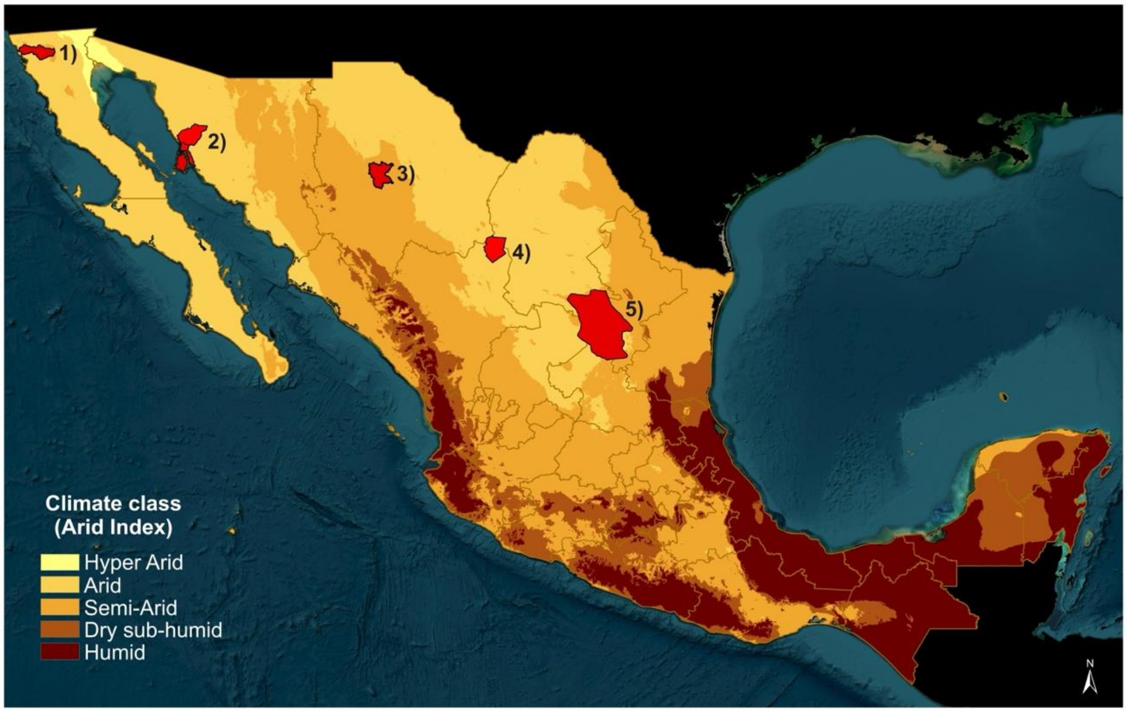


Fig. 1.1 Geographical location of the Social-Ecological Participatory Observatories: 1) Guadalupe, 2) Comcaac, 3) Cuauhtémoc, 4) Mapimí and 5) El Tokio.

With the projected escalation in aridity and the anticipated rise in the frequency of drought occurrences across global drylands, the prevalence of abiotic factors governing land degradation could intensify (Ravi et al. 2010). However, while land degradation is a global problem, it takes place locally and requires local solutions (Cherlet et al., 2018). In this context, understanding the effects of climate change on precipitation at the local level poses challenges for research to comprehensively encompass the diverse impacts on local drylands social-ecological systems.

Recent efforts to promote participatory research have resulted in the realization of face-to-face and virtual workshops to identify the main problems within the OPSEs. In March 2021, a survey was conducted between the diverse stakeholders that make up the five OPSEs to identify the priority issues and/or problems that should be addressed within each OPSE. The results showed that drought, climate change and water scarcity are the main problems that should be addressed. At the end of March 2021, OPSE Mapimí held a second meeting, with the aim of concluding the exercises of the previous workshop. One of the problems associated with drought was the lack of monitoring of the phenomenon, so the participating sectors (academics, local communities, government) concluded that a monitoring network of environmental variables such as rainfall, temperature, wind speed, etc. should be created and drought indicators such as the standardized precipitation index should be used.

However, since the OPSEs are physical and virtual sites/spaces where new knowledge is collected, exchanged and co-generated a spatial delineation of boundary or boundaries is required for that multiple stakeholders and local landowners can prioritize areas with respect to value to space to implement action strategies to address the problems identified collectively. Numerous scholars worldwide have proposed various methodologies for identifying the basic units of SES and mapping interactions between ecological and social sub-systems to elucidate the intricate dynamics of SES. These methodologies include mapping SES through anthropogenic biomes (or anthromes) (Ellis and Ramankutty, 2008), identifying land system archetypes (Václavík et al., 2013), delineating ecoregions (Castellarini et al., 2014) or bundles of ecosystem service use (Hamann et al., 2015). However spatially explicit exercises for mapping SES boundaries at local scale are still scarce (Martín-Lopez et al., 2017).

An alternative method for analyzing SES involves examining the social valuation of multiple through the sense of place, specifically through meaningful places (Martinez and Torres, 2013; 2018; Knaps et al., 2022). The meaningful places are geographic locations, both in the physical world and in abstract representation on maps to which certain meanings are ascribed to when immediately perceived or socially constructed (e.g., with a series of adjectives, descriptions of place characteristics, symbolic attributions) or evaluative attachments are tied to (place dependence, place identity) (Knaps et al., 2022).

In this dissertation, I addressed three main topics i) the social, environmental and economic value linked to shared land associated with OPSE by multiple stakeholders and ii) the future changes of the precipitation and the potential occurrence of droughts under climate change conditions in the context of the network of OPSE in the drylands of northern Mexico. This thesis is structured in five chapters with chapters two, three and four addressing the above key topics:

In **Chapter 2,** I present a new approach, based on multi-stakeholders mapping of meaningful places, to jointly identify the social, environmental and economic values linked to shared land as a basis to co-define the boundaries of social-ecological systems. As a case study, I developed the complex mechanism of spatial delimitation in the context of the OPSE Mapimí situated in the UNESCO Man and the Biosphere Reserve. In particular, I addressed the following research questions:

1. What criteria do different stakeholder groups prioritize with respect to relating value to space and how does this influence the identification and distribution of meaningful places in the OPSE Mapimi?

2. How can different stakeholder maps of meaningful places be integrated to delineate the boundary or boundaries of the shared space and based on the spatially assigned values of the land what socio-environmental characteristics of potential social-ecological units may emerge for the OPSE Mapimi?

In **Chapter 3,** I explore the importance of drought monitoring at the local level in the context of the OPSE. Drought monitoring relies on good quality meteorological data, but data recording frequently faces problems. Dryland areas commonly lack a representative network of meteorological stations or suffer from incomplete climate recordings; this applies for large areas in Mexico. However, the evaluation and potential use of global precipitation databases are an underexplored opportunity for the identification, characterization, and projection of increasingly occurring extreme weather phenomena, like the droughts, which are fundamental to learn about at the local level for local stakeholders and decision-makers to develop adaptation strategies. I addressed the following questions:

1) How do globally available precipitation products perform in Mexican drylands considering different basin areas associated with the OPSE network?

2) How does data quality of each precipitation product vary at different temporal scales in the context of the OPSE?

In **Chapter 4,** I examine the occurrence (frequency, severity and duration) of historical and future droughts at a particular time scale (12 months) at regional scale in the OPSE network using the Standardized Precipitation Index (SPI). Likewise, the perception of the concept of drought and the adaptation measures are analyzed in the OPSE Mapimí. In particular, I addressed the following questions:

To what extent will the projected meteorological drought become more frequent and sever during the 21st century for the OPSE network?

How do the local communities perceive the drought concept and what main strategies of adaptation have been adopted when facing the risks of droughts in the OPSE Mapimí?

The dissertation offers a comprehensive and practical approach, which could be implemented in other regions, with or without data availability.

1.4 References

Berkes, F. and Folke, C. 1998. Linking social and ecological systems. Cambridge University Press, Cambridge, UK.

Bernardino, P. N., De Keersmaecker, W., Horion, S. et al. 2025. Predictability of abrupt shifts in dryland ecosystem functioning. Nature Climate Change. 15, 86–91. https://doi.org/10.1038/s41558-024-02201-0

Biggs, R., Clements, H., de Vos, A., Folke, C., Manyani, A., Maciejewski, K., Martín-López, B., Preiser, R., Selomane, O., and Schlüter, M. 2021. What are social-ecological systems and social- ecological systems research? In: Biggs, R., de Vos, A., Preiser, R., Clements, H., Maciejewski, K., Schlüter, M. 2021. The Routledge handbook of research methods for social-ecological systems. Taylor and Francis Group. Available online: https://library.oapen.org/handle/20.500.12657/49560

Brandt, P., Ernst, A., Gralla, F., Luederitz, C., Lang, D. J., Newig, J., Reinert, F., Abson, D. J., von Wehrden, H. 2013. A review of transdisciplinary research in sustainability science. Ecological Economics 92, 1-15, https://doi.org/10.1016/j.ecolecon.2013.04.008

Burrell, A. L., Evans, J. P. and De Kauwe, M. G. 2020. Anthropogenic climate change has driven over 5 million km^2 of drylands towards desertification. Nature Communications, 11, 3853. https://doi.org/10.1038/s41467-020-17710-7

Carpenter, S. R., Folke, C., Norström, A., Olsson, O., Schultz, L., Agarwal, B., Balvanera, P., Campbell, B., Castilla, J. C., Cramer, W., DeFries, R., Eyzaguirre, P., Hughes, T. P., Polasky, S., Sanusi, Z., Scholes, R. and Spierenburg, M. 2012. Program on ecosystem change and society: an international research strategy for integrated social-ecological systems. Current Opinion in Environmental Sustainability 4(1):134-138. https://doi.org/10.1016/j.cosust.2012.01.001

Castellarini, F., Siebe, C., Lazos, E., de la Tejera, B., Cotler, H., Pacheco, C., Boege, E., Moreno, A. R., Saldívar, A., Larrazábal, A., Galán, C., Casado, J. M., Balvanera, P., 2014. A social-ecological spatial framework for policy design towards sustainability: Mexico as a study case. Investigación Ambiental 6, 45–59. Available in: https://www.aacademica.org/eckart.boege/16.

Cherlet, M., Hutchinson, C., Reynolds, J., Sommer, S., von Maltitz, G., 2018. World Atlas of Desertification. Third ed. Publication Office of the European Union, Luxembourg https://doi.org/10.2760/9205

Clark, W. C., van Kerkhoff, L., Lebel, L., Gallopin, G. C. 2016. Crafting usable knowledge for sustainable development. Proceedings of the National Academy of Sciences 113(17):4570-4578. https://doi.org/10.1073/pnas.1601266113

Costello, M. J. et al. 2022. Cross-chapter paper 1: biodiversity hotspots. In Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change 2nd edn, Vol. 3 (eds. Pörtner, H.-O.) Ch. 2123–2161. Cambridge University Press

Cornwall, A. and Jewkes, R. 1995. What is participatory research? Social Science & Medicine 41 (12), 1667-1676. https://doi.org/10.1016/0277-9536(95)00127-S

de Albuquerque, F. S., Macías, R. M. A., Búrquez, A., Barreto, C. A. de M. 2024. Potential effects of climate change on cacti distribution and conservation in North American drylands. Journal of Arid Environments 226, 105282. https://doi.org/10.1016/j.jaridenv.2024.105282

Ellis, E. C., Ramankutty, N., 2008. Putting People in the Map: Anthropogenic Biomes of the World. Frontiers in Ecology and the Environment, 6(8), 439-447. https://doi.org/https://doi.org/10.1890/070062.

Feng, S. and Fu, Q. 2013. Expansion of global drylands under a warming climate Atmospheric Chemistry and Physics. 13, 14637–1466. https://doi.org/10.5194/acp-13-10081-2013

Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T. and Rockström, J. 2010. Resilience Thinking: Integrating Resilience, Adaptability and Transformability. Ecology and Society 15 (4): 20. www.ecologyandsociety.org/vol15/iss4/art20

Folke, C., Jansson, Å., Rockström, J., Olsson, P., Carpenter, S. R., Chapin III, F. S., Crépin, A.-S., Daily, G., Danell, K., Ebbesson, J., Elmqvist, T., Galaz, V., Moberg, F., Nilsson, M., Österblom, H., Ostrom, E., Persson, Å., Peterson, G., Polasky, S., Steffen, W., Walker, B. and Westley, F. 2011. Reconnecting to the Biosphere. Ambio 40 (7):719-738. http://dx.doi.org/10.1007/s13280-011-0184-y

Folke, C., Biggs, R., Norström, A. V., Reyers, B. and Rockström, J. 2016. Social-ecological resilience and biosphere-based sustainability science. Ecology and Society 21(3):41. http://dx.doi.org/10.5751/ES-08748-210341

Fu, B., Stafford-Smith, M. and Fu, C. 2024. Editorial overview: Dryland social-ecological systems in changing environments. Current Opinion in Environmental Sustainability, 48:A1–A5. https://doi.org/10.1016/j.cosust.2021.03.001

Hamann, M., Biggs, R., Reyers, B., 2015. Mapping social-ecological systems: identifying 'green-loop' and 'red-loop' dynamics based on characteristic bundles of ecosystem service use. Global Environmental Change 34, 218–226, https://doi.org/10.1016/j.gloenvcha.2015.07.008.

Higham, I., Bäckstrand, K., Fritzsche, F. and Koliev, F. 2024. Multistakeholder Partnerships for Sustainable Development: Promises and Pitfalls. Annual Review of Environmental Resources. 49: 475–500, https://doi.org/10.1146/annurev-environ-051823-115857

Hoover DL, Knapp AK, Smith MD. 2014 Resistance and resilience of a grassland ecosystem to climate extremes. Ecology 95 (9):2646–2656. https://doi.org/10.1890/13-2186.1

Huang, J., Yu, H., Guan, X. et al. 2016. Accelerated dryland expansion under climate change. Nature Clim Change 6, 166–171. https://doi.org/10.1038/nclimate2837

Huang, J., G. Zhang, Y. Zhang, X. Guan, Y. Wei, and R. Guo. 2020. Global Desertification Vulnerability to Climate Change and Human Activities. Land Degradation & Development 31, no. 11: 1380–1391. https://doi.org/10.1002/ldr.3556.

Huber-Sannwald, E., Martínez, T. N., Espejel, I., Lucatello, S., Coppock, D. L. & Reyes Gómez, V. M. 2020. Introduction: International Network for the

Sustainability of Drylands. Trasndisciplinary and Participatory Research for Dryland Stewardship and Sustainable Development. In: Huber-Sannwald, E., Martínez, T. N., Espejel, I. Lucatello, S., Coppock, D. L. & Reyes Gómez, V. (eds.) Stewardship of Future Drylands and Climate Change in the Global South. pp. 1-24. Springer International Publishing, India. https://doi.org/10.1007/978-3-030-22464-6

IPCC, 2019. Special Report on Climate change and Land. Chapter 3. Desertification. Available online: https://www.ipcc.ch/srccl/

Knaps, F., S. Gottwald, C. A., Herrmann, S., 2022. Using meaningful places as an indicator for sense of place in the management of social-ecological systems. Ecology and Society 27(4): 9. https://doi.org/10.5751/ES-13340-270409.

Koutroulis, A. G. 2019. Dryland changes under different levels of global warming. Science of the Total Environment 655, 482–511. https://doi.org/10.1016/j.scitotenv.2018.11

Koppa, A., Keune, J., Schumacher, D. L., Michaelides, K., Singer, M., Seneviratne, S. I. and Miralles, D. G. 2024. Dryland self-expansion enabled by land–atmosphere feedbacks. Science 385, 967-972 https://doi.org/10.1126/science.adn6833

Lauterio, M. C. L., Huber-Sannwald, E., Hernández, V. S. D., Leyva, A. J. C., Lucatello, S., Martínez, T. N., Mata, P. R. I., Reyes, G. V. M. and Seingier, G. 2021: Métodos colectivos para tejer el camino desde la desertificación al desarrollo sostenible: Los Observatorios Participativos Socio-Ecológicos. Ecosistemas, 30, 2232. https://doi.org/10.7818/ECOS.2232

Liu et al. 2007. Complexity of coupled human and natural systems. 317, 5844. 1513-1516. https://doi.org/10.1126/science.1144004

Maestre F. T., Eldridge, D. J., Soliveres, S. et al., 2016. Structure and functioning of dryland ecosystems in a changing world. Annual Review of Ecology, Evolution and Systematics, 47:215–237. https://doi.org/10.1146/annurev-ecolsys-121415-032311

Martín-Lopez, B., Palomo, I., García L. M., Iniesta A. I., Castroe, A. J., García Del Amo, D., Gómez B. E., Montes, C., 2017. Delineating boundaries of social-ecological systems for landscape planning: A comprehensive spatial approach. Land Use Policy 66, 90–104. http://dx.doi.org/10.1016/j.landusepol.2017.04.040.

Martínez, T. N., Torres, L.A., 2013. Arqueología Comcáac: El Paisaje Cultural a través del tiempo. Creel, paper presented at 1er Congreso Internacional CarlLumholtz. culturas, geografías y temporalidades", Los nortes de México.

Martínez, T. N., Torres, C. L. A. 2018. Walking the desert, paddling the sea: Comcaac mobility in time. Journal of Anthropological Archaeology 49, 146–160. https://doi.org/10.1016/j.jaa.2017.12.004.

Merçon, J. 2022. Investigación transdisciplinaria e investigación-acción participativa en clave decolonial. Utopía y Praxis Latinoamericana, 27 (98),https://doi.org/10.5281/zenodo.6614174

Middleton, N. and Thomas, D. 1997. (Eds): World Atlas of Desertification. University of Oxford, UK

Mirzabaev, A., L.C. Stringer, T.A. Benjaminsen, P. Gonzalez, R. Harris, M. Jafari, N. Stevens, C.M. Tirado, and S. Zakieldeen. 2022. Cross-Chapter Paper 3: Deserts, Semiarid Areas and Desertification. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2195–2231, doi:10.1017/9781009325844.020.

Raymond, C. M., Fazey, I., Reed, M., Stringer, L. C., Robinson, G. M., Evely, A. C. 2010. Integrating local and scientific knowledge for environmental management: from products to processes. Journal of Environmental Management 91:1766-1777.

Ravi, S., Breshears, D. D., Huxman, T. E., D'Odorico, P. 2010. Land degradation in drylands: Interactions among hydrologic–aeolian erosion and vegetation dynamics. Geomorphology 116(3–4):236–245 https://doi.org/10.1016/j.geomorph.2009.11.023

Rockström, J., W. Steffen, K. Noone, Å. Persson, F. S. Chapin III, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. A. Foley. 2009. A safe operating space for humanity. Nature 461 (7263):472-475. https://doi.org/10.1038/461472a

Rockström, J. 2016. Future Earth. Science 351(6271):319. https://doi.org/10.1126/science.aaf2138

Rockström, J., Donges, J. F., Fetzer, I. et al. 2024. Planetary Boundaries guide humanity's future on Earth. Nat Rev Earth Environ 5, 773–788. https://doi.org/10.1038/s43017-024-00597-z

Safriel, U. et al. 2005. Dryland Systems. In: Ecosystems and human well-being: current state and trends / Hassan, R., Scholes, R., Ash, N., Washington: Island Press - ISBN 9781559632287 - p. 623 - 662

Scheffer, M., Barrett. S., Carpenter, S. R. et al. 2015. Creating a safe operating space for iconic ecosystems. Science 347:1317–1319. https://doi.org/10.1126/science.aaa3769

Stafford Smith, D.M., Abel, N., Walker, B., Chapin, F.S. 2009. Drylands: Coping with Uncertainty, Thresholds, and Changes in State. In: Folke, C., Kofinas, G., Chapin, F. (eds) Principles of Ecosystem Stewardship. Springer, New York, NY. https://doi.org/10.1007/978-0-387-73033-2_8

Stavi, I., Roque de Pinho, J., Paschalidou, A. K., Adamo, S. B., Galvin, K., de Sherbinin, A., Even, T., Heaviside, C., & van der Geest, K. 2022. Food security among dryland pastoralists and agropastoralists: The climate, land-use change, and population dynamics nexus. The Anthropocene Review, 9(3), 299-323. https://doi.org/10.1177/20530196211007512

Steffen et al., 2004. Global Change and the Earth System: a Planet under Pressure. Springer-Verlag, New York, New York, USA.

Steffen, Will, Paul J. Crutzen, and John R. McNeill. 2007. “The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature?” Ambio 36, no. 8: 614–21. http://www.jstor.org/stable/25547826.

Steffen, W., Persson, Å., Deutsch, L., Zalasiewicz, J., Williams, M., Richardson, K., Crumley, C., Crutzen, P., Folke, C., Gordon, L., Molina, M., Ramanathan, V., Rockström, J., Scheffer, M., Schellnhuber, H. J. and Svedin, U. 2011. The Anthropocene: from global change to planetary stewardship. Ambio 40(7):739-761. https://doi.org/10.1007/s13280-011-0185-x

Stott, P. 2016. How climate change affects extreme weather events. Science 352(6293):1517–1518

Tengö, M., E. S. Brondizio, T. Elmqvist, P. Malmer, and M. Spierenburg. 2014. Connecting diverse knowledge systems for enhanced ecosystem governance: the multiple evidence base approach. Ambio 43 (5): 579-591. https://doi.org/10.1007/s13280-014-0501-3

Tengö, M., Hill, R., Malmer, P., Raymond, C. M., Spierenburg, M., Danielsen, F., Elmqvist, T., and Folke, C. 2017. Weaving knowledge systems in IPBES, CBD and beyond—lessons learned for sustainability. https://doi.org/10.1016/j.cosust.2016.12.005

UN (United Nations). 2015. Transforming our world: The 2030 agenda for sustainable development. A/RES/70/1 Available online: https://sdgs.un.org/sites/default/files/publications/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf

Václavík, T., Lautenbach, S., Kuemmerle, T., Seppelt, R., 2013. Mapping Global Land System Archetypes. Global Environmental Change, 23 (6), 1637-1647. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2013.09.004.

Vicente-Serrano, S.M., Pricope, N.G., Toreti, A., Morán-Tejeda, E., Spinoni, J., Ocampo-Melgar, A., Archer, E., Diedhiou, A., Mesbahzadeh, T., Ravindranath, N.H., Pulwarty, R.S. and Alibakhshi, S. 2024. The United Nations Convention to Combat Desertification Report on Rising Aridity Trends

Globally and Associated Biological and Agricultural Implications. Glob Change Biol, 30: e70009. https://doi.org/10.1111/gcb.70009

WBG (World Banl Group) 2015. Sustainable Development Goals Annual Report. Available online: https://documents1.worldbank.org/curated/en/106391567056944729/pdf/World-Bank-Group-Partnership-Fund-for-the-Sustainable-Development-Goals-Annual-Report-2019.pdf

Yan, Z., Guo, Y., Sun, B., Gao, Z., Qin, P., Li, Y., Yue, W., and Cui, h. 2024. Combating land degradation through human efforts: Ongoing challenges for sustainable development of global drylands. Journal of Environmental Management 354, 120254. https://doi.org/10.1016/j.jenvman.2024.120254

Yirdaw, E., Tigabu, M. and Monge, A. 2017. Rehabilitation of degraded dryland ecosystems—review. Silva Fennicca. 51, 1673 https://doi.org/10.14214/sf.1673

Chapter 2

---

2. Multi-stakeholder mapping of meaningful places – a novel entry point to collectively value, care for and delineate shared land

2.1 Abstract

Defining the boundaries of social-ecological systems is becoming increasingly important both for integrated sustainable land use planning and land use policy development and by tackling this synergistically considering a multi-stakeholder perspective. Participatory mapping tools allow the identification of diverse spatial elements including the invisible and often intangible values different stakeholders associate with certain places within a shared land. We addressed the questions: What criteria do different stakeholders prioritize with respect to relating value to space and how does this influence the identification and distribution of meaningful places in the OPSE Mapimi? How can different stakeholder maps of meaningful places be integrated both to delineate the boundary or boundaries of the shared space and based on the spatially assigned values of the land what socio-environmental characteristics of potential social-ecological units may emerge for the OPSE Mapimi? This chapter presents a new joint mapping approach to integrate different stakeholder maps to allow for the delineation of the boundary or boundaries and new social-ecological units of the shared space at the social-ecological participatory observatory of the UNESCO Mapimí Biosphere Reserve in Northern Mexico. The methodology is a five-step approach: (1) stakeholder mapping of

meaningful places; (2) relief morphometric classification; (3) delineation of social-ecological participatory observatory; (4) characterization of social-ecological units, and (5) validation of results by the same stakeholder groups. The integrated spatial information reflects the highly diverse and complex human-environment interactions and the multi-dimensional value of land that prevails in the study area both at the local and regional scale. The meaningful places were mostly associated with the environmental quality category; they were distributed in the subhorizontal plains (flat plains), undulating plains and hilly plains. The methodological framework allowed to define the spatial boundaries of a social-ecological participatory observatory and the social-ecological units at local scale. The advantage of this approach is that it allows the integration of cartographic data available (hydrology, cover, land use, etc.) and information unavailable (social, economic, health, culture, recreation, etc.) collected through meaningful places mapping. The advantage of this approach is that it allows the integration of available cartographic data (hydrology, cover, land use, etc.) and unavailable information (social aspects, health, culture, recreation, etc) collected by mapping meaningful places. This mapping exercise is of great utility for policy makers and local landowners and users because it allows prioritizing areas with respect to shared value of space and to implement action strategies to effectively and collectively address the problems and interests. In addition, this mapping exercise allowed perform a collective appraisal of perceptions, experience, interest and knowledge of multiple stakeholders over the shared space allowing identifying areas of common relevance and represents a transferable and replicable approach. Because it represents an overview of current local and environmental conditions, this approach represents a dynamic process that can open up new possibilities for collective action by integrating more multi-stakeholders.

Keywords: meaningful places; participatory GIS, boundary, social-ecological units

2.2 Introduction

The concept of the social-ecological systems (SES) articulates the intricate interactions between the environmental subsystem (ES) and the societal/human subsystem (SS) and was introduced by Berkes and Folke in 1998. Since then, the SES approach has become central in global academic discourse (Liu et al., 2007; Ostrom, 2009; Sterk et al., 2017) and has undergone substantial evolution resulting in theoretical and methodological advancements (Herrero et al., 2018; Colding and Barthel, 2019; Biggs et al., 2021). In the past, efforts to model ES have focused on the conservation of biodiversity and ecosystem services taking advantage of global-scale satellite data to map the spatio-temporal dynamics of these services (Naidoo et al., 2008; Sinare et al., 2016; Qu and Lu, 2018; López et al., 2024). Important resources have been allocated to employ remotely sensed data to effectively capture these dynamics (Martínez-Harms et al., 2016; Choudhary et al., 2018; Li et al., 2024) emphasizing that the benefits of ecosystem services extend beyond local administrative boundaries and often have transregional impacts across both time and space (Pascual et al., 2017).

Inversely, for the SS, i.e. spatial, temporal, socio-demographic and perceptional information related to urban and rural activities have been used to develop detailed models that interpret human behavior by aggregating and categorizing social and economic functions at various scales (Minet et al., 2017; Niu and Silva, 2020). However, country-level databases, e.g. on population density, security, health, culture, etc., concerning the SS are often outlined or delimited at different administrative levels, such as municipality, state, or national and this information is not consistently available in vector format (i.e. spatially explicit information for use in geographic information systems) (INEGI, 2024). Since SES research is centered on the relationships/connections between subsystem components, i.e., the human and the environmental system components, rather than detailed studies of isolated subsystems, data integration and synthesis between different data formats across various scales is one of the critical challenges of the SES modelling (Elsawah et al., 2020).

The regionalization of basic socio-environmental units boundaries is crucial in defining SES (Feng & Koch, 2024). Because the fractal nature of SES, Brunckhorst et al. (2006) support that social-ecological dynamics can be spatially represented at different nested scales. Many SES studies follow a similar data pre-processing approach, first integrate multi-scale data to determine a layer of spatial unit boundaries and then measure, evaluate, analyze, predict, or optimize underlying variables based on these units (Rocha et al., 2020). This layer of spatial unit boundaries defines the resolution to which all data attributes are adjusted and, ultimately, the scale of the analysis. For (spatial) SES analyses, defining spatial boundaries of the basic units is a prerequisite to accurately represent and ultimately understand the interactions and feedback between humans/society and the environment in these intertwined systems (Elsawah et al., 2020). Numerous scholars worldwide have proposed various methodologies for identifying the basic units of SES and mapping interactions between ecological and social sub-systems to elucidate the intricate dynamics of SES. These methodologies include mapping SES through anthropogenic biomes (or anthromes) (Ellis and Ramankutty, 2008), identifying land system archetypes (Václavík et al., 2013), delineating ecoregions (Castellarini et al., 2014) or bundles of ecosystem service use (Hamann et al., 2015; Martín-Lopez et al., 2017).

Other studies delineate areas where human-perceived landscape values coincide with physically measured ecological values (Alessa et al., 2008). This approach permits matching social-ecological patches with certain landscape units usually named using local terminology (Sinare et al., 2016). In another studies, social-ecological units were distinguished by categorizing different village types by their unique species (plants, butterflies and birds) diversity patterns (Hanspach et al., 2016) or by combining multivariate analysis of biophysical and socio-economic variables with GIS techniques (Martín-Lopez et al., 2017). Recently, a variety of machine learning techniques including unsupervised Bayesian network classifiers (Ropero et al., 2021), top-down rule-based classification methods based on a multi-criteria evaluation (Yang et al., 2023) and K-means clustering algorithm (Deng and Cao, 2023) have been applied to facilitate the quantification of similarities among different SES and the categorization of geographic units that exhibit high levels of similarity into corresponding clusters (Yang et al., 2021).

An alternative method for analyzing SES involves examining the social perception and valuation of multiple stakeholders to enable policymakers to enact impactful measures (Fischer et al., 2015). Perception refers as defined by Schermerhorn et al. (2000), like processes “wherein people select, organize, interpret, retrieve and respond to the information from the world around them”, producing mental impressions and constructions which will ultimately help shape behaviors and actions. While valuation refers to the values that people, ascribe to things, i.e., the process of assessing the value of something (Bengston, 1994). This implies values, beliefs, attitudes and norms that influences human behavior (Botzat et al., 2016). Therefore, analyze the multidimensional value of shared land through participatory mapping of meaningful places based in the deep understanding, experience and knowledge of multiple stakeholders is a promising approach.

The engagement of multiple stakeholders promotes interactive learning, mutual empowerment and participatory governance. This enables stakeholders with related problems and ambitions, yet at times with competing interests, to be collectively innovative and resilient when facing emerging risks, crises and opportunities in complex and changing environments (Brouwer and Woodhill, 2016). Current research highlights the “sense of place” as a promising concept considering the management of SES (Verbrugge et al., 2019; Knaps et al., 2022) and to support environmental conservation and management as a product of transdisciplinary multi-stakeholder collaboration (Duggan et al., 2024). “Sense of place” refers to people’s interpretative perspectives on and emotional reactions to their environments (Hummon, 1992); or it refers to a place-relation that is felt to be deeply important and thus is interpreted to be meaningful (Stokowski, 2008). The sense of place is a highly complex concept that scholars have operationalized in various ways through time, e.g. place identity (Proshansky et al. 1983), favourite place (Korpela, 1992), place attachment (Altman and Low, 1992) and meaningful place (Martinez and Torres, 2013; 2018; Gatersleben et al., 2020; Knaps et al., 2022).

Each of these complex holistic concepts comprises a range of affective and behavioral dimensions such as specific behavior, feelings, memories, perceptions and social connections with specific places; hence they have been increasingly advocated to support the management of SES (Gatersleben et al., 2020). Knowing the sense of place of different stakeholder groups also helps to deal with place-related conflicts (Clermont et al., 2019) to better understand supportive, indifferent, or hostile behavior (Gottwald and Stedman, 2020), or permits comparing the views of different stakeholders (in)directly involved with and subject to territorial reorganization (Stoffelen et al., 2024). Because of increased human mobility and globalization, individuals interact with many places near and far to satisfy their desires and needs. This perception of shared land opens new opportunities to motivate place-based approaches of stewardship at different scales including approaches with well-defined boundaries at local scale (Chapin and Knapp, 2015).

For this study, we adopted the concept “meaningful places” (Martinez and Torres, 2013; 2018; Knaps et al., 2022). They are geographic locations, both in the physical world and in abstract representation on maps to which certain meanings are ascribed to when immediately perceived or socially constructed (e.g., with a series of adjectives, descriptions of place characteristics, symbolic attributions) or evaluative attachments are tied to (place dependence, place identity) (Knaps et al., 2022). This concept is powerful as it permits the capture of the invisible and often intangible meanings people hold for certain places, which can be depicted in a spatially explicit way with participatory mapping tools (Müller et al., 2020). We propose mapping the meaningful places of a shared land may provide frequently unaccounted for insight and representation of the social perception and valuation of different stakeholder groups. With this information we further propose to jointly define the spatial boundary of a Social-ecological Participatory Observatory (OPSE, Spanish acronym). An OPSE is understood as a living laboratory in a shared territory, which facilitates transdisciplinary processes, i.e. the co-generation of useful knowledge related to a certain SES, where joint pathways of action are explored with participatory methodologies (Lauterio et al., 2021).

While several researchers have proposed general frameworks for delineating SES boundaries that integrate environmental conditions, socioeconomic indicators, and land-use patterns (Kumar et al., 2021), as well as biodiversity considerations (Lazzari et al., 2019) or separate aspects of ES and SS (Martín-López et al., 2017). To our knowledge no study has yet integrated insights of multiple stakeholders through the mapping of meaningful places as a basis to identify and spatially map the diverse possible boundary or boundaries of an OPSE. This delineation is essential for it determines the joint scale or scales of interest at which representative information of different social-ecological areas is intended to be collected or monitored so that it is representative of the different social-ecological systems found within the area of interest (Bourgeron et al., 2018). While sustainability-oriented laboratories in real-world have been described (McCrory et al., 2020), comprehensive studies on these laboratories that integrate sustainability considering the social perceptions and valuation of different stakeholder groups with the goal to collectively value and care for shared land, appear lacking.

To address the above-mentioned research gap, we argue that a multi-stakeholder mapping approach of meaningful places of a shared space needs to be replicable at diverse scales and capable of generating useful insight for decision-making that extends beyond the traditional boundaries of municipalities, or communal lands, among others. Also, we emphasize the need to adopt an inclusive approach which considers the knowledge, experience, perception and valuation of multiple stakeholders as a starting point to collectively value and care for shared land, and after this valuation help to channel efforts towards the improvement of the territory (considering government programs, research projects, monitoring protocols, among others) and allow to define priority areas for conservation, subsistence farming, restoration, ecosystem service production, among others, for present and for future generations. We address the following research questions: What criteria do different stakeholders prioritize with respect to relating value to space and how does this influence the identification and distribution of meaningful places in the OPSE Mapimi? How can different stakeholder maps of meaningful places be integrated to delineate the boundary or boundaries of the shared space and based on the spatially assigned values of the land what socio-environmental characteristics of potential social-ecological units may emerge for the OPSE Mapimi? In this study, we present a new approach, based on multi-stakeholders mapping of meaningful places, to jointly identify the social-ecological values linked to shared land as a basis for co-defining the boundaries of social-ecological systems.

2.3 Materials and Methods

2.3.1 Study área

In 2019, the Social-ecological Participatory Observatory (OPSE) Mapimí was founded in association with the Biosphere Reserve of Mapimí (BRM) situated in the state corners area of Durango (62.89%), Coahuila (22.45 %) and Chihuahua (14.67 %) in the central part of the Chihuahuan Desert (Fig. 2.1). The BRM was decreed in 1977 as a UNESCO Man and the Biosphere (MAB) Reserve, marking the beginning of the biosphere reserve program in Mexico. This reserve was the first created and recognized by UNESCO's MAB program in Latin America (Halffter, 1984). Biosphere reserves are expected to promote conservation of the genetic diversity of species, research, environmental monitoring, training and education in their management plans (CONANP, 2006; Reyes et al., 2021).

The BRM extends over 342,387 ha and constitutes an endorreic basin with elevations between 1000 m and 1480 m a. s. l. (Garcia, 2002). In the BRM, soils are of alluvial and colluvial origin; the most common soils are calcareous regosols, xerosols, yermosols, and saline vertisols (Delhoume 1992). The climate is arid mostly with summer rainfall regime (July to September). For the period 1978–2021, average annual rainfall was 256 mm, of which 54% correspond to summer precipitation and 9% to the winter precipitation (December–February); the largest recorded annual rainfall was 600 mm and the lowest 25.1 mm. The average annual temperature is 20.8 °C with a normal monthly minimum of 7.8 °C in the month of January and a normal monthly maximum of 30.3 °C in the month of June (SMN, 2024).

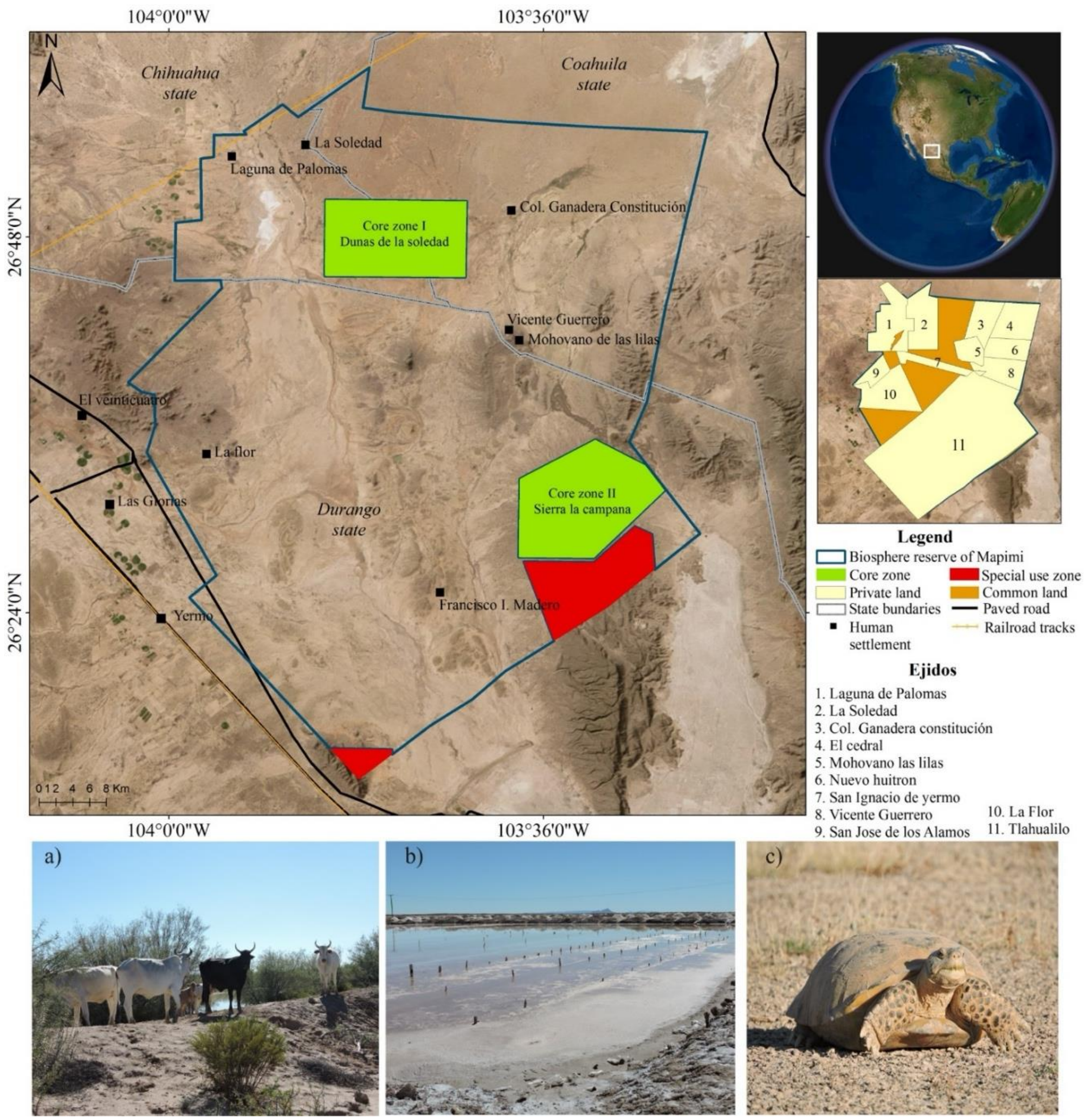


Fig. 2.1. The map depicts the location of the Biosphere Reserve of Mapimí (main map) in the Chihuahua Desert in Mexico including its political division considering

communal (ejidos) and private land (center right). The pictures present the main economic activities of the BRM: (a) extensive livestock production (b) artisanal salt production, and (c) ecotourism.

In the BRM, the vegetation is characterized by xerophytic scrubland (Chihuahuan desert scrubs) and halophytic grasslands; their species composition depends mainly on the slope, soil water availability, salinity, and soil texture, among other features (Grünberger et al., 2004). The xerophytic scrubland is widely distributed in the BRM; it is characterized by shrub species forming a wide variety of plant associations (Garcia, 2002). The most abundant shrub species are Larrea tridentata, Prosopis gandulosa, Opuntia rastrera, Acacia constricta and Fouqueria splendens, among others. While the halophytic grassland extends in areas with high salt concentrations; the two most abundandant grass species are Sporobolus airoides and Pleuraphis mutica. The vascular flora consists of approximately 71 families, 242 genera and 403 species (Garcia, 2002).

The fauna includes 270 vertebrate species and approximately 200 bird species. The fauna includes the Bolsón tortoise (Gopherus flavomarginatus), an endemic species with conservation priority, as well as the desert fox (Vulpes macrotis) and the dune lizard (Uma paraphygas), which are within the conservation risk category (NOM-059-SEMARNAT-2001). Migratory birds temporarily rest and nest in the BRM; four of these species have special protection status, six are considered threatened, and one is in danger of extinction (NOM-059-SEMARNAT-2001) (CONANP, 2006). From a historical and cultural point of view, the area has important vestiges and manifestations, such as rocks or sedimentary deposits with fossils, cave paintings from indigenous cultures (Chichimecas-Tobosos), archeological stone circles of unknown function, arrowhead carving sites, and ruins of haciendas from colonial times (CONANP, 2006). The main socio-economic activities in the BRM are extensive cattle ranching, artisanal salt production and more recently, ecotourism (Figure 2.1) (Hernández, 2001).

Since 2002, the BRM has been managed by the National Commission of Protected Natural Areas (CONANP, Spanish acronym) with the dual purpose of ecosystem conservation and human development. This situation generates complex dynamics shaping the reserve's SES considering both conservation policies and economic activities of the primary and tertiary sectors carried out by the local inhabitants (Toledo, 2005; Martínez et al., 2020). The BRM, consists of 11 "ejidos" (the Mexican communal land tenure system) and three private properties (Figure 2.1); the current total population of the reserve is 326 (CONANP 2006; Huber-Sannwald et al., 2020). They live in small, isolated settlements; the overall low population density is explained by high emigration rates mostly due to the lack of educational opportunities inside of the reserve (Martínez et al., 2020). Recently, several governmental, academic and NGO institutions have organized and joined efforts to protect the natural, cultural and social diversity of the BRM and to strengthen its social-ecological resilience to climate change and land degradation (Huber-Sannwald et al., 2020). Hence, the BRM is currently a space of participatory research and monitoring and contributes to the accomplishment of the Sustainable Development Goals in Mexico's drylands (Reyes et al., 2021).

2.3.2 Multidimensional spatial data collection and analysis

The methodology for multi-stakeholder mapping of meaningful places to collectively value and care for shared land, was structured in five steps (Fig. 2.2): (1) mapping of meaningful places (Knaps et al., 2022), (2) relief morphometric classification, a process of regionalization of the territory based on landscape units where the starting point was the geomorphological delimitation (Priego et al., 2010), (3) delineation of OPSE boundary based on the integration of stakeholder maps of meaningful places, the relief morphometric classification and thematic maps (hydrology and land use and vegetation) through Geographic Information System (GIS), (4) demarcation of social-ecological units and (5) validation of results by participants of the same stakeholder groups.

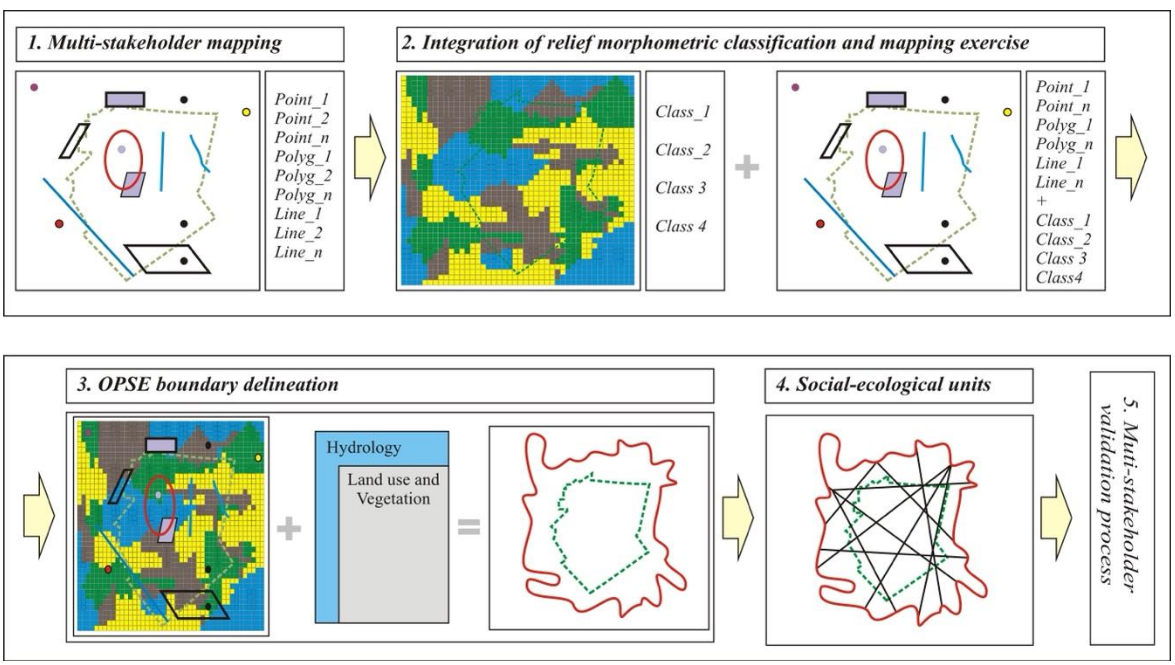


Fig. 2.2. Step-by-step methodological pathway for mapping meaningful places to delineate the boundary of the Social-ecological Participatory Observatory: 1) multi-

stakeholder mapping of meaningful places, the symbols (line, point and polygon) indicate the type of spatial information collected; 2) Integration of classification of geoforms (mountains, hills and plains) adapted to the study area by the vertical dissection method (Priego et al., 2010) and meaningful places mapping; 3) Delineation of potential spatial boundaries of OPSE between step 3 and thematic maps defined by the participants (hydrology, land use/vegetation cover) using map overlay techniques, 4) quantification of social-ecological units using overlay map techniques (results from steps 1, 2, 3) and, 5) validation of results by the participants.

2.3.2.1 Step 1: Multi-stakeholder mapping of meaningful places

To identify and locate the meaningful places for each stakeholder group in the study area, 14 mapping events were held between October 2021 and March 2022. To select participants, an inventory of stakeholders was carried out to identify local communities (ejidos), academics, government and non-government institutions with local influence (economic activities or research) in the study area. In the case of local communities, adults were selected who are currently living in the BRM or who have been performing all or part of their economic activities in the BRM. For academics, government and non-governmental institutions, only those were selected who counted with at least five years of experience working or acting in the BRM. Due to the SARS-CoV-2 pandemic, face-to-face and virtual workshops were conducted (Fig. 2.3). For face-to-face mapping events, nine events were performed with local communities (total of 31 people), one event with government representatives of the CONANP (two people) and one event with academics (one person). In each workshop, we applied participatory mapping using two printed maps, one of the ejido (resolution varied from 1:24000 to 1:106000) and one of the BRM (1:120000). The printed maps were spread on a table to allow easy access to all participants. Sufficient time was allocated for participants to familiarize themselves with the image and to situate themselves spatially (Figure 2.3 a, b). Each mapping excercise took approximately 1.5 to two hours.

In case of the virtual mapping events, two workshops were organized with academics of distinct affiliations and one with a non-governmental organization (one person). We applied participatory mapping using the Public Participation Geographic Information System (PPGIS) platform (FELT, 2021). An introductory explanation of the operation of the PPGIS platform was given. This platform made it possible to generate geo-referenced information for later use in GIS (Figure 2.3, c, d). Each virtual event took approximately two hours.

Fig 2.3. Multi-stakeholder mapping of meaningful places using printed maps with the governmental organization CONANP (a), and local community members (b); and virtual mapping with a non-governmental organization (c) and academics using PPGIS (d).

To map the meaningulf places, the participants were prompted with guiding questions that included information on the distinct values and definitions of meaningful places (Table 2.1); the value typology used was adapted from Brown and Reed (2000) and Cerveny et al. (2017). The facilitator recited the full list of meaningful place category and their definitions prior to the mapping. For this exercise, participants were asked to identify all those places on the map that were meaningful or important to them. Each place was marked as a point, line, or polygon depending on the size of the selected site. There was no limit to the number of meaningful places they could identify; one particular place could be associated with different categories of meaningful places. They used both their ejido map and the BRM map to mark meaningful places. They were provided with the BRM map in case there were significant places outside the ejido. We decided not to restrict the mapping of meaningful places at the scale of ejido and BRM. If there were meaningulf places ouside of the two maps, the location(s) and its (their) description(s) were noted on a sheet of paper by the facilitator.

We acknowledge that the identification of meaningful places may represent sensitive information/knowledge of the participants; therefore, at each event we excluded those places from the exercise. The participants collectively selected the meaningful places they did not want to be considered in the data analysis. Those meaningful places were identified on the map but not added to the final list of meaningful places. Aproximately three meaningful places were excluded from analysis because of privacy issues related to important vestiges and manifestations, such as rocks or sedimentary deposits with fossils and cave paintings. Upon completion of the maps, the points, lines and polygons created by each stakeholder group were geo-referenced using a geographic information system.

Table 2.1. Categories of meaningful places and their definition (Brown and Reed, 2000; Cerveny et al. 2017).

Meaningful place	Definition
Esthetic	I value this place for the scenery, sights, smells or sounds
Economic	I value this place, because it provides income and employment opportunities through trade, meat and salt sale, ecotourism, among others. I value this place because it is are directly related to my work (investigation, exclusion sites, restoration sites, etc).
Environmental quality	I value this place, because it helps produce, preserve, and renew air, soil and water or it contributes to healthy habitats for plants and animals
Future	I value this place, because it allows future generations to know and experience as it is now
Health	I value this place, because it provides a place where I or others can feel better physically and/or mentally
Heritage	I value this place, because it has natural and human history that matters to me, and it allows me to pass down the wisdom
Home	I value this place, because it is my home and/or I live here
Learning	I value this place, because it provides a place to learn about, teach, or research the natural environment
Recreation	I value this place, because it provides outdoor recreation opportunities or a place for my favorite recreation activities
Social	I value this place, because it provides opportunities for getting together with my friends and family or is part of my family's traditional activities
Spiritual	I value this place because it is sacred, religious, or spiritually special to me

Subsistence	I value this place because it provides food and other products to sustain my life and that of my family

For the virtual mapping events, the facilitator proceeded in the same way as for the face-to-face meetings. In the PPGIS platform, the participants could choose the spatial representation mode (point, line, or polygon) to designate meaningful places on the map including a description of the value of the place. For example, the government organization identified an area of turtle habitat and explained that it was important for annual turtle population monitoring. In the PPGIS platform, the scale of the map was not fixed, allowing participants to freely zoom in and out for place designation. We decided not to restrict the mapping of meaningful places at the scale of MBR, in order to maximize space association, such that the participants could mention and map as many or as few places as they perceived to be meaningful. The points, lines and polygons were downloaded in the *.GeoJSON format and imported into GIS (ArcMap 10.4.1). Afterwards, all meaningful places identified during the face-to-face and virtual mapping events were spatially integrated. In addition, an excel file was generated for each mapping event with the list of places, the value associated with the category and its value description. This allowed the identification of places of common relevance among the different participants as well as the number of categories for which the place was mentioned. This file also made it possible to eliminate repeated meaningful places, and to concentrate a final list of places, but which included all the information from the virtual and face-to-face mapping excercises.

A frequency analysis (percentage) according to category was performed including all meaningful places. The final list of meaningful places was plotted depicting the number of times and category that a particular meaningful place was stated. For the analysis, the meaningful places were classified into three main categories: population center (urban or rural), large areas (areas larger than 0.5 hectares) and small areas (areas less than 0.5 ha.). With the number of categories associated to the meaningful places, a density map was performed in ArcMap 10.4.1 to spatially highlight areas or zones of collective value considering all stakeholder groups.

2.3.2.2 Step 2: Morphometric relief classification

Mountains, hills and plains are common geoforms in Mexican territory. These geoforms were described and typified using Vertical dissection (Vd), which refers to the difference between the highest and lowest altitudinal point measured in m/km^2 (Priego et al., 2010). The conventional relief morphometric classification identifies 13 different classes of mountains, hills and plains (Spiridonov, 1981). This classification was adapted to Mexico using the scales 1:50,000 and 1:250,000 (Priego et al., 2010). To link meaningful places to the relief, we used the 1:250,000 scale, which reported five types of relief. According to the Vd dissection (Vd) our study area fell in the five relief types, subhorizontal plain (Dv $\leq$ 2.5), undulating plain (2.6 $<$ Vd $<$ 15), hilly plain (16 $<$ Vd $<$ 40), hills (41 $<$ Vd $<$ 100), and mountains (Vd $\geq$ 100) (Priego et al., 2010). For this classification, several Digital Elevation Models (DEM) were downloaded from the US Geological Survey (USGS, 2022) Earth explorer platform (https://earthexplorer.usgs.gov/). The DEM used was SRTM 1 Arc-Second Global. This elevation data offers worldwide coverage of void filled data at a resolution of 30 meters and provides open access to this high-resolution global data set (USGS, 2018). A 12 DEM mosaic was created covering the area of the BRM.

2.3.2.3 Step 3: Identification of spatial boundary of Social-Ecological Participatory Observatory

The multidimensional spatial data derived from the mapping events were integrated with the relief morphometric classification in ArcMap 10.4.1. The spatially explicit distribution of the meaningful places was then matchd with the associated relief (first approximation). Afterwards, an overlay mapping technique was performed with two thematic maps: hydrology and land use/vegetation cover. These layers were used because at times participants referred to some meaningful places without defining a specific spatial extension, e.g., the grasslands have a wide distribution in the study area, or surface runoff, which presents a topographic demarcation.

Based on the spatial distribution of the meaningful places and when the morphometric class was territorially extensive and no meaningful place was identified by the participants, and then the relief could not be used to define the spatial boundary of the OPSE. Consequently, both the hydrological aspect (basin) was used to demarcate the spatial boundary. However, both the hydrological aspect (basin) and the land use/vegetation cover map were used to define the spatial boundary of the OPSE always considering the presence of meaningful places. This integration of all stakeholder maps of meaningful places with the relief morphometric classification, hydrology and land use/vegetation cover maps allowed a first approximation of the boundaries of the OPSE. However, meaningful places were also scattered in municipalities, states or countries outside of the BRM. This situation made it possible to delineate two boundaries of the OPSE. The first corresponds to the maximum concentration of meaningful places mapped, spatial area that could be considered as the main working area of the OPSE, and the second boundary could be considered as an area of influence subject to updating and following-up on the objectives of the OPSE, such as expansion of the observatory, implementation of research projects, governmental support, among others.

2.3.2.4 Step 4: Identification of spatial Social-Ecological Units (SEU) in the OPSE

We identified social-ecological units (SEU) within the OPSE Mapimi by determining the spatial co-occurrence of similar biophysical variables (hydrology, land use/vegetation cover, relief) and socio-economic variables (via meaningful places mapping). The concept of SEU is taken from Martin-Lopez et al. (2017) who characterized the co-ocurrence between an ecological and socio-economic regionalization at ecodistrict level, the polygons obtained represent the SEU at local scale. In addition, the methodology of García et al. (2005) was considered, who define a hierarchical scheme or classification system of environmental units, based on the concurrent spatial patterns of various combinations of environmental factors, which are represented cartographically. In this chapter, the objective of characterizing the SEU was to determine the areas of greatest relevance to the different stakeholders and to subsequently identify common problems or interests with these units such that actions could be taken collectively.

We defined a hierarchical of classification system of social-ecological units (SEU) (Table 2.2) based on the concurrent spatial distribution of hydrology, land use/vegetation cover, relief and meaningful places. According to this classification system, the BRM was divided into terrestrial environments: this classification is due to the fact that the delimitation of environmental units can be applied to a coastal environment; System, comprising five relief types; Subsystem, comprising five hydrological basins; Social-ecological unit divided into 12 different land use and vegetation cover, and finally the value or definition of meaningful place divided into12 types. With GIS, a map of SEUs was generated superimposing thematic maps adopting the hierarchical scheme or classification system considering the geomorphological map (at scale 1:50,000), surface hydrology (at scale 1:50,000), land use/vegetation cover series VII (at scale 1: 250,000) INEGI (2018) and the meaningful places mapped. In the case of land use/vegetation cover, the layer was grouped into primary classes, for example: halophytic grassland, induced grassland, natural grassland, secondary shrub vegetation of halophytic grasslands and secondary shrub vegetation of natural grasslands, was classified only as grassland (Table 2.1S). The reason for simplifying the classes is that if the original polygons of the land use/vegetation cover layer are considered, a very large number of socio-ecological units would be obtained.

Table 2.2 Hierarchical social-ecological unit classification system used in this study based on the thematic layers selected.

Environment	System (geomorphology) (USGS, 2022)	Sub-system (basin) (INEGI, 2023)	Social-ecological unit (land use and vegetation cover) (INEG, 2018)	Meaningful place category
Terrestrial	1. Sub-horizontal plain 2.Undulating plain 3. Hilly plain 4. Hills 5. Mountains	I. La India – Cerro gordo stream II. Laguna de Palomas III. Laguna del Rey IV. La Cadena stream V. Nazas river – Santa Rosa channel	A. Irrigated agriculture B. Rainfed agriculture C. Water-bodies D. No apparent vegetation E. Pine-oak-tascate forest F. Mesquite woodland G. Chaparral H. Desert scrub I. Grassland J. Urban area K. Sandy deserts L. Gypsophilous-halophytic vegetation	a. Esthetic b. Economic c. Environmental quality d. Future e. Health f. Heritage g. Home h. Learning i. Recreation j. Social k. Spiritual l. Subsistence

Subsequently, the integrative description of each SEU considers the cartographic and non-cartographic information available. An example of a SEU is synthesized in table format (Table 2.3) and additional information is presented in the Table 2.2S.

Table 2.3. Example of the description of a social-ecological unit (# 78) within the OPSE Mapimi. The key description corresponds to the classification systems: cosidering environment, geomorphology, hydrology, land use/vegetation cover, and categories of meaningful places.

Social-ecological unit: # 78	Key: 3.II.A.abcdefghijk
Environment	Terrestrial
Geomorphology	Hilly plain
Basin	Laguna de Palomas
Land use/vegetation cover	Gypsophilous Halophilic vegetation
Meaningful place category	Esthetic, economic, environmental quality, future, health, heritage, home, learning, recreation, social and spiritual
Ejido	La Flor, San Jose de los Álamos, N.C.P.E. Tlahualilo.
Municipality	Mapimí, Tlahaualilo
Aquifer	Ceballos

2.3.2.5 Step 5: Validation of the boundaries of OPSE and of the approximation of the generation of social-ecological units

To validate the results obtained in the identification of OPSE boundaries and SEU, we conducted face-to-face and virtual workshops with the participants between September 2022 and February 2023, following the same order as the participatory mapping exercises. The validation exercise with the academic sector, governmental and non-governmental institutions was conducted virtually. In these events, an explanation and standardization/adaptation of technical terms (geomorphology, land use and vegetation and superimposition techniques maps) to local terms was performed mainly in case of participants of local communities. The standardization of terms was necessary for the participants to understand what source information was used to generate both the OPSE borders and the SEU, how it was processed, what type of results were obtained and the potential usefulness of the information generated. After the standardization/translation of technical terms to local knowledge was accomplished, a guided discussion was held considering the following questions: Are the meaningful places identified by your sector correctly mapped (spatial location)? Do you consider that the proposed boundaries for the delineation of the OPSE are appropriate? Can you suggest any aspect or variable that should be considered additionaly to improve the OPSE boundaries? Do the social-ecological units contain the social-environmental elements that you naturally identify in your daily activities? According to your productive/economic activities, are the proposed SEUs distributed in a representative way? Are the SEU in their current categorization and thus distribution likely useful for you to monitor the impact of your activity (e.g, livestock production, salt production, ecotourism, academic research, soil restoration)? Are these SEU potentially useful for your and other stakeholder group? All comments and suggestions from the participants were collected and incorporated into the results section in narrative form.

2.4 Results

2.4.1 Descriptive analisys of mapping meaningful places

As a collective, 622 meaningful places were identified in the Mapimi Biosphere Reserve. Local communities identified 57% of the meaningful places, the academic sector 28%, the government agency 8% and the nongovernment agency 7%. Each stakeholder group identified the three main categories of meaningful places; the local communities selected the economic, subsistence, and environmental quality categories; the academic sector selected the learning, environmental quality and esthetic categories; the government agency selected environmental quality, economic and social categories; and the non-governmental organization selected learning, esthetic and environmental quality categories.

In all mapping events, there were more female participants (59%). Participation was successful, as each participant identified at least one meaningful place; some meaningful places were identified by more than one participant summing up to a total of 267 distinct meaningful places (i.e., of the total number of 622 meaningful places, many were mentioned repeatedly by different stakeholders). The total meaningful places are describe in the Table 2.3S. Overall, environmental quality and economic categories were selected most frequently (each with 14 %), followed by learning and subsistence (each with 13 %), together accounting for 54 % of all meaningful places in the study area (Fig 2.4). Of the 12 potential categories, all were selected except for future value.

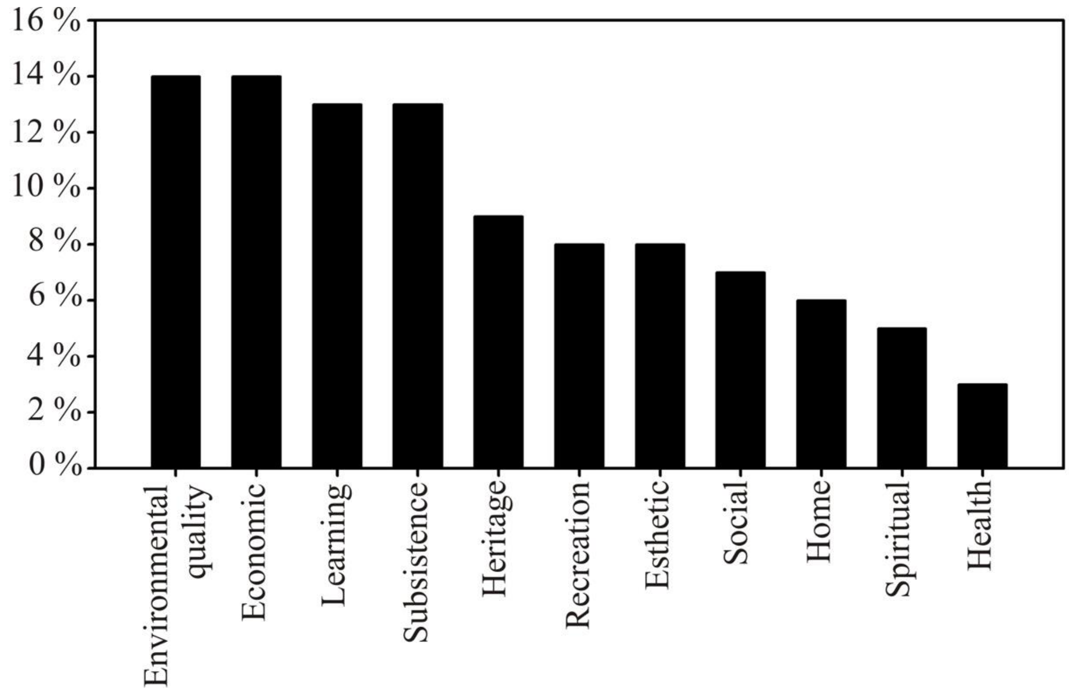
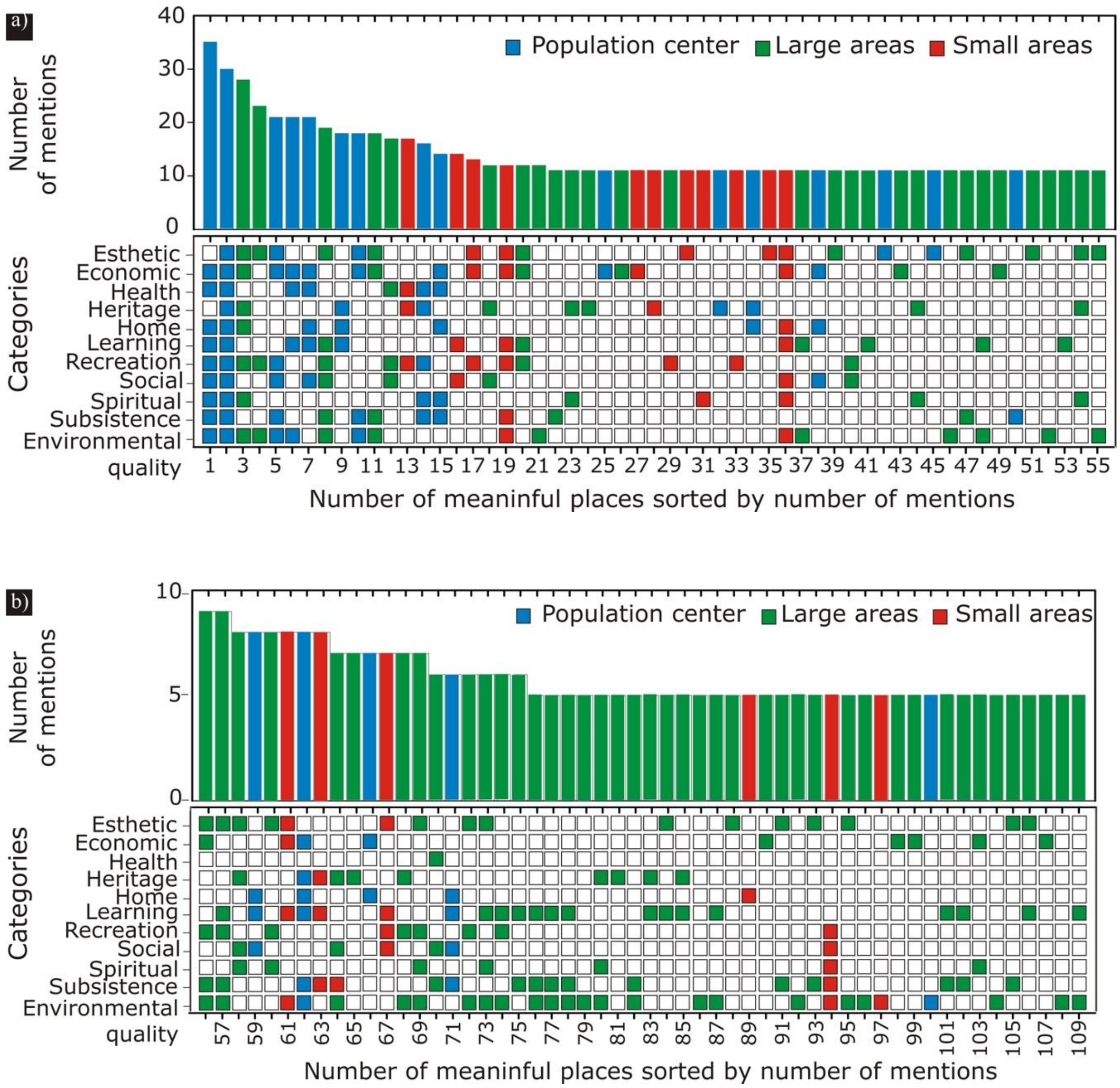
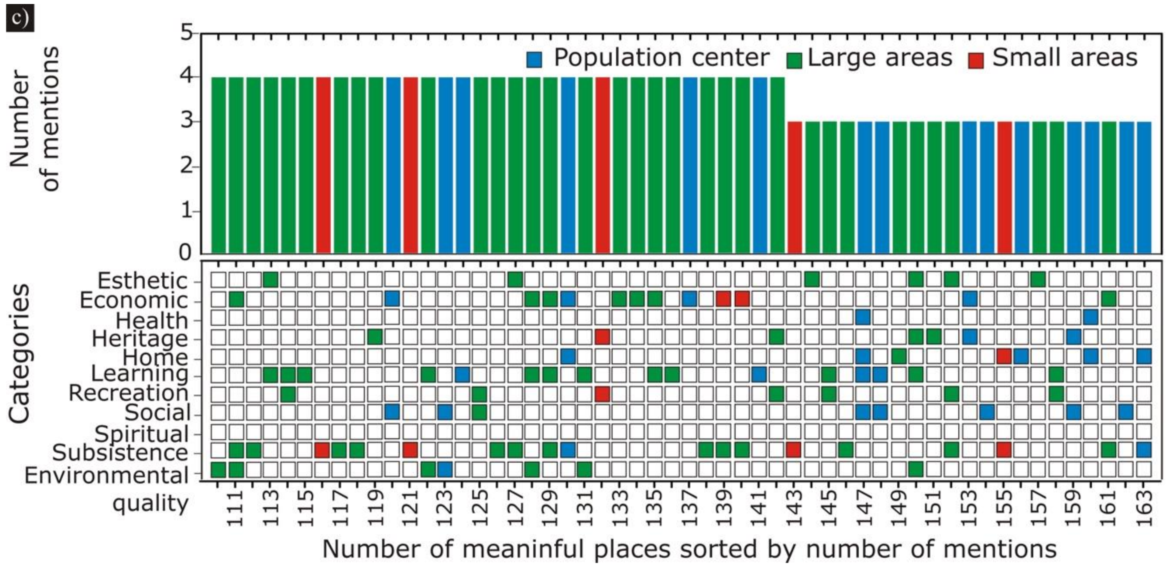
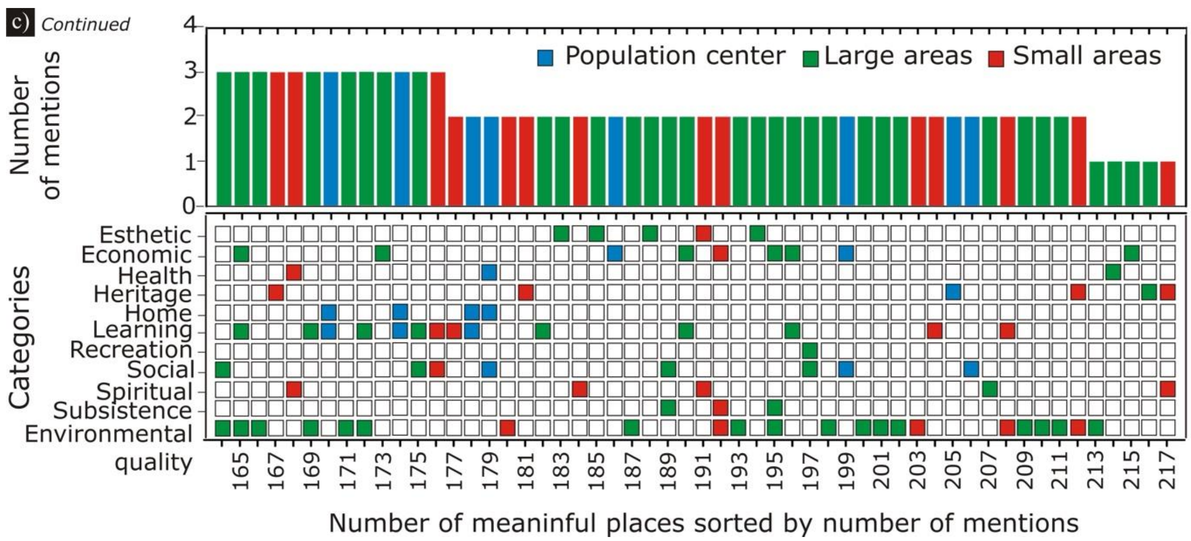


Fig. 2.4. Frecuency (percentage) distribution of the 11 categories of meaningful places selected by four stakeholder groups (local communities, government agency, non-governmental organization, and academics) for the Mapimi Biosphere Reserve in Northern Mexico, during 14 mapping workshops (total number of distinct meaningful places = 267).

The meaningful places most frequently mentioned by the participants were: 1) Ceballos, a small urban area just outside of the BRM where the local community members from the ejidos of the BRM and other stakeholder groups develop diverse economic activities (Fig. 2.5a; bar 1); it is the center of food supply, health service, schools, recreation, and religion, among others. 2) The ejido La Flor located close to the administrative border inside of the BRM; it has the visitor center of the BRM, which serves as a focal point for participatory multi-stakeholder workshops, capacity building, and local organizational meetings for the communities belonging to the BRM; there the academic sector, the government agency CONANP, and the non-governmental organization HABIO promote participatory research and other monitoring or restoration projects (Fig. 2.5a; bar two). 3) The BRM represents an area of identity and belonging to local communities; this is related to training, monitoring, use, and conservation of resources associated with their ejidos (Fig. 2.5 a, bar three).




c)
Number of mentions
Population center
Large areas
Small areas
Categories
Esthetic
Economic
Health
Heritage
Home
Learning
Recreation
Social
Spiritual
Subsistence
Environmental quality
Number of meaninful places sorted by number of mentions


c) Continued
Number of mentions
Population center
Large areas
Small areas
Categories
Number of meaninful places sorted by number of mentions

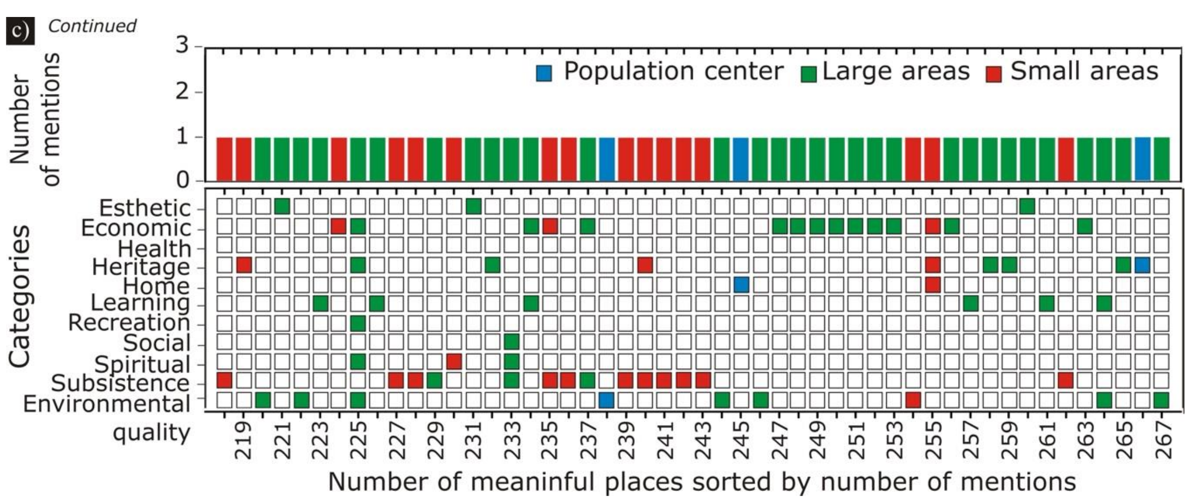

c) Continued
Number of mentions
Population center
Large areas
Small areas
Categories
Number of meaninful places sorted by number of mentions

Fig. 2.5. The bar graph indicates the meaningful places sorted by the number of times they were mentioned by the participants. Meaningful places mentioned a) 11 to 40 times, b) 5 to 10 times, and c) 1 to 4 times. Blue bars indicate a population center, green bars indicate large areas and red bars indicate small areas. The grid below the bar graph indicates the categories in which the meaningful place was classified.

The free interaction wih the maps made it possible to identify meaningul places not only in areas surrounding the BRM, but also in more distant regions, including other states and countries (Fig. 2.6b).

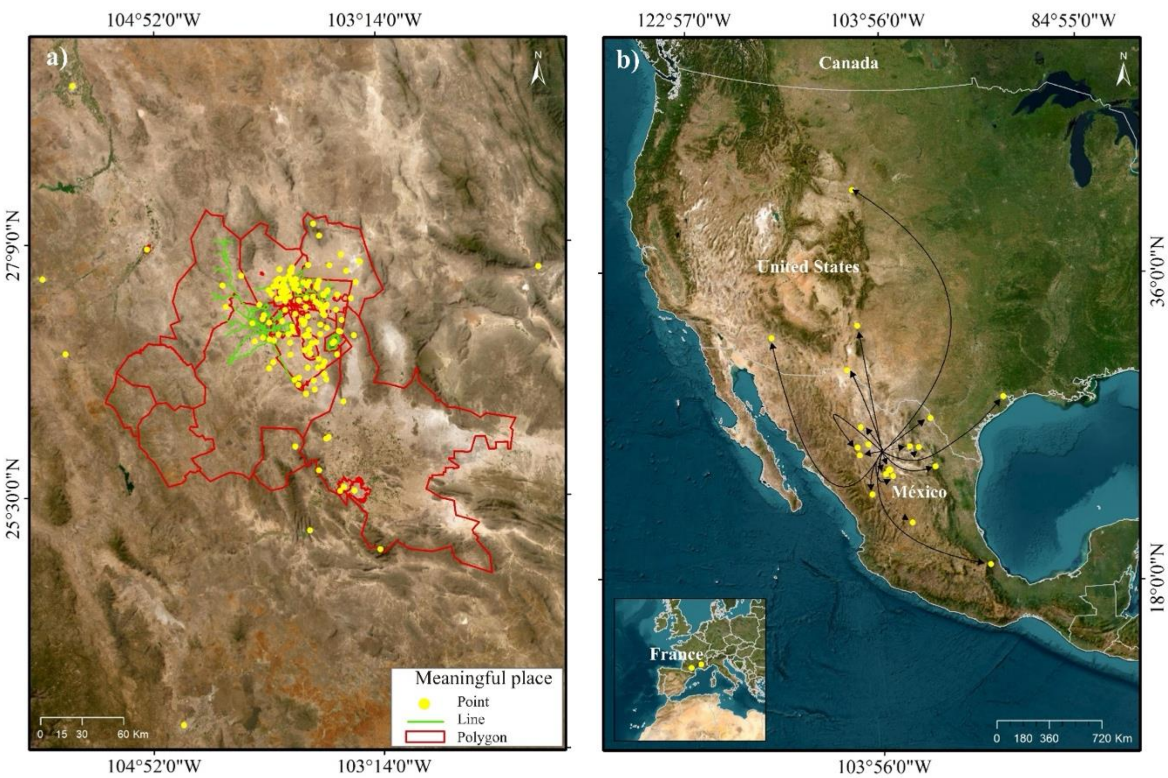


Fig 2.6. Spatial depiction of meaningful places (points, lines and polygons) a) inside and outside of the Biosphere Reserve Mapimi, and b) located in other cities, states, and countries as a product of participatory mapping by four stakeholder groups (local communities, government agency, non-government agency and academics).

2.4.2 Spatial distribution of meaningful places in a topographic context

Meaningful places identified by the different sectors are mainly distributed in the sub-horizontal plains ($Vd \leq 2.5$), undulating plains ($2.6 < Vd < 15$) and hilly plains ($16 < Vd < 40$) (Fig. 2.7a). Indeed, most meaningful places are concentrated within the administrative polygon of the BRM (Fig 2.6). The BRM is one of the three places (besides Ceballos and La Flor ejido) most frequently identified as a meaningful place, being stated 28 times and with relevance in seven categories of social-ecological significance (Fig 2.5a). To identify the areas with the highest concentration of meaningful places, a density map was generated (Fig. 2.7b). Two areas emerged as zones of concentration of meaningful places: the area of influence witin and just outside of the BRM and the urban areas of Gomez Palacio and Torreón South of the BRM. The connection and mobility to these urban areas is related to better access to and supply of goods and services, for example, educational and health institutions, family homes, recreation points, shopping centers, among others. The polygons of the BRM and relevant aquifers are shown independently in the Fig. 2.7 a) and b) for reference in comparison to the distribution of the meaningful places.

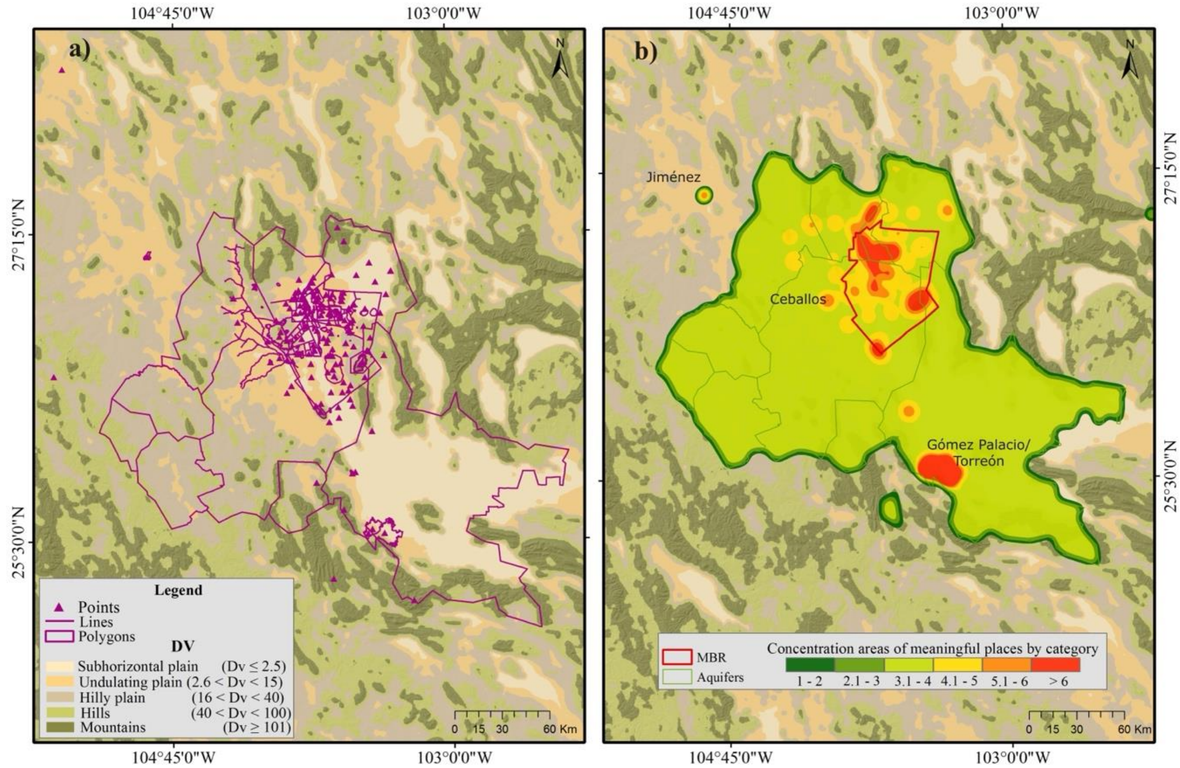


Fig 2.7. a) Geomorphological classification according to the vertical dissection method with three modes of spatial representation (points, lines and polygons) of meaningful places in the Biosphere Reserve Mapimi. b) Heat map depicting the areas with the highest concentration of meaningful places (red) based on the number of categories identified per meaningful place by four stakeholder groups.

2.4.3 Boundaries of the MBR OPSE

The integration of the spatial distribution of the meaningful places, the geomorphological units in which the meaningful places are embedded, surface and subsurface hydrology, as well as land use/vegetation cover together determined the boundaries of the OPSE. It is important to note that most of the mapped places are concentrated inside of the political-administrative area of the BRM. The spatial social-ecological boundary of the OPSE is a result of integrating biophysical variables of socio-environmental significance according to the mapping exercise of the stakeholders. The boundary is dynamic, not static, as it may undergo modifications depending on actor perspectives, changing interests, among others (Fig 2.8a). The OPSE boundary considers a second spatial social-ecological boundary considered the buffer zone; it includes meaningful places outside of the BRM corresponding to the flow of knowledge acquisition or exchange, social coexistence, or acquisition of goods and services (health, education, religion, food) denoting the relevance of this area by the stakeholder groups (Fig. 2.8b).

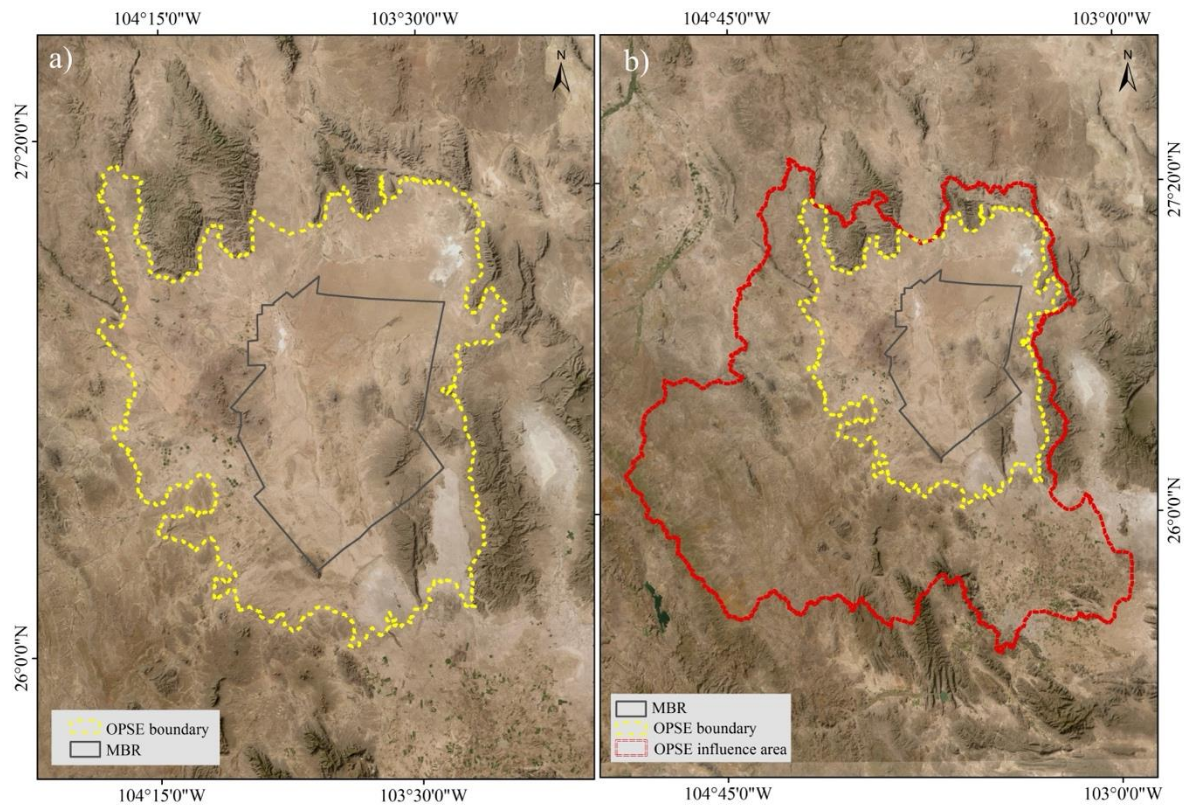


Fig. 2.8. Spatial extent of the Social-Ecological Participatory Observatory (OPSE) of the BRM derived from participatory mapping and intersection of thematic maps. a) The dotted yellow line represents the dynamic and flexible boundary suggesting that the definition of the boundary is open and dynamic and subject to potential future

updates and re-evaluations. b) The solid red line represents the maximum spatial extent of the OPSE, which includes urban areas of Gomez Palacio and Torreon (see Figure 2.7b), both meaningful places selected by the stakeholders.

2.4.4 Social-ecological units with the OPSE

Within the spatial extent of the OPSE (1,056,110.00 ha), a total of 113 social-ecological units (Table 2.4S) were generated by superimposing different thematic maps (geomorphology, surface hydrology, land use/vegetation cover, and spatial location of meaningful places) (Fig. 2.9a). Due to the number of SEUs generated, three units were extracted to show the SEUs and and its characteristics (Fig 2.9b). Depending on the scales used, some SEUs may have the same hydrology but different coverage, or even some SEUs may maintain the same spatial distribution, e.g. urban areas or water bodies, therefore, these units may remain as a meaningful place. The SEU number 5 correspond to grassland areas siatuated in subhorizontal plains where the main activity is the extensive cattle ranching. The SEU number 15 corresponds to the urban zone (Ceballos), where all stakeholders develop their economic activities and have access to resources and services. The SEU number 91 correspond to hills and mountains covered by desert scrub; this zone of MBR is characterized by high biological diversity. Table 2.4S contains the numbering of the resulting SEU as well as their corresponding attributes.

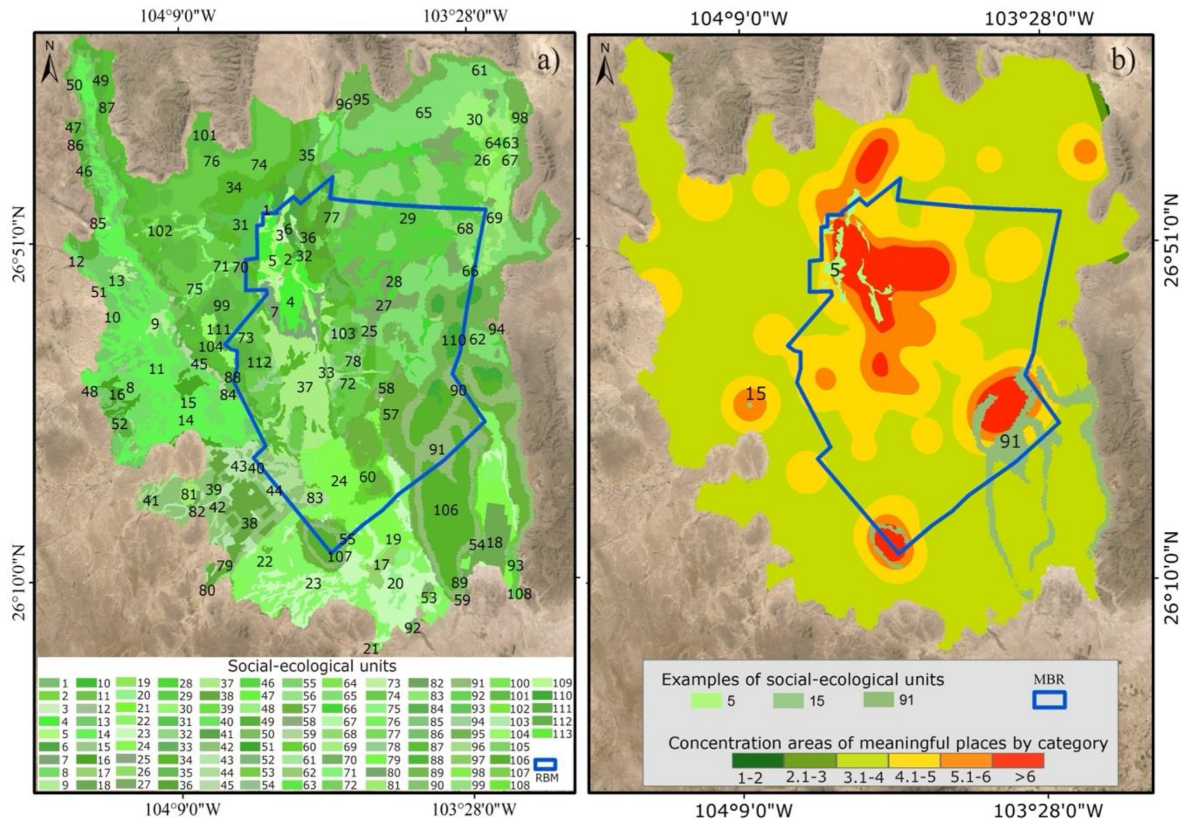


Fig. 2.9. a) Spatial distribution of 113 social-ecological units characterizing the Social-ecological participatory Observatory (OPSE) associated with the Biosphere Reserve Mapimi in Central Mexico, derived from superimposition techniques of the thematic maps. b) Shows the spatial distribution of the social-ecological units (SEU) 5, 15 and 91 and the heat for highlight which units are of greatest collective relevance among the participating sectors.

2.4.5 Validation of OPSE boundaries and social-ecological units

Technical terms were standardized with local terms, so that the process could be satisfactorily understood. For example, the sub-horizontal plains, which are the lowest parts of the relief, were described as “los bajos” (in Spanish) or the areas devoid of vegetation were described as “barreales” (in Spanish). This exercise was also used to explain the processes of overlapping layers to define the opse boundary.

All stakeholder groups agreed on the proposed spatial limits of the OPSE as a first approximation of an immediate area of action, belonging and care of shared land, for future programs such as monitoring fauna and flora, conservation, ecotourism and rangeland management for organic meat production. With respect to the proposed area mapped outside of the BRM, all stakeholder groups agreed in that should be considered as an area of influence for the first delimitation.

A point to highlight is that the four stakeholder groups acknowledged the identified limits of the OPSE obey the perception of the current group of actors, and that these perceptions may need to be modified over time. Participants representing the governmental sector stated the great value of this approximation, as it reflects the social-ecological knowledge and interests of all stakeholder groups. They suggested adopting this approach as a potential justification for expanding the Biosphere Reserve Mapimí.

They also mentioned that if each SEU had some identified problem, it would be easier to carry out intervention measures for improvement. The local communities stated that the social-ecological units have great value for efforts on future environmental education and wildlife monitoring activities. Meanwhile, the livestock sector recognized that these SEU spatially converge between communal or private properties, so there should be an agreement between cattle ranchers to use this spatial delimitation efficiently.

2.5 Discussion

The analysis of SES has undergone substantial evolution, reflecting great theoretical and methodological advances (Colding and Barthel, 2019), however spatially explicit exercises for mapping SES boundaries are still scarce (Castellarini et al., 2014; Hamann et al., 2015; Martín-Lopez et al., 2017; Ropero et al., 2021). Despite these developments, methodological approaches that include multi-stakeholder perceptions and knowledge continue to be a great challenge when wanting to depict a shared social-ecological system. Hence, it is absolutely critical that all stakeholders participate in a joint effort to develop effective policies, practices, knowledge and governance in a socially equitable and inclusive form (Fisher et al., 2015). Our study presents an analytical approach to incorporate the multidimensional values of shared land through participatory mapping of meaningful places based in the deep understanding, experience and knowledge of multiple stakeholders is a transferable and replicable approach.

This work demonstrate that analyzing the multidimensional value of shared land through participatory mapping of meaningful places based in the deep understanding, experience and knowledge of multiple stakeholders is a transferable and replicable approach. The methodology can be applied at different spatial scales. While the spatial extent of BRM was regional, the spatial extent and scale of the meaningful places varied. In the face-to-face mapping exercises, members from local communities, who carry out environmental education or ecotourism activities, identified meaningful places only within their ejido or, in some cases, in nearby ejidos.

Academics and governmental institutions (with research, monitoring and conservation activities) mapped meaningul places at ejido and BRM scales.

On the other hand, we found that some participants had difficulty spatially associating meaningful places considering online and face-to-face mapping. In the face-to-face mapping, the degree of association with space seemed easier for men than for women. This argument was supported by some participants, who mentioned that most men (specifically cattle ranchers) are more mobile than women as they cross territories between ejidos and private properties more frequently than women. Women in contrast are more engaged in activities such as fauna monitoring, environmental education and ecotourism, where they focus in great detail on specific areas, which could possibly limit the level of integration and/or spatial association. In virtual mapping, some participants had difficulties in the management of the web platform and in identifying meaningful places in a spatial context. In both cases, the facilitator helped resolve these difficulties. Other studies have mapped meaningful places but have not differentiated or analyzed the level of spatial association among participants (men and women) (Cerveny et al., 2017; Muller et al., 2020).

Our data gathering approach differs from some studies, in that participants are typically required to limit the number of meaningful places (five places) (Cerveny et al., 2017). This limitation of place selection is because each participant had to choose the meaningful places and write why the place was important, but the response space was confined (Cerveny et al., 2017). Our face-to-face and virtual mapping exercises were subject to several limitations and did not work as expected:

(i) disposition (willingness or available time) of some stakeholders to participate in the mapping exercises, (ii) lack of integration of some local communities in the exercise, (iii) small resolution of the printed maps mainly at ejido scale and (iv) difficulties of some participants to spatially associate the meaningful places on the web platform or on printed maps. We believe despite some limitations that are planned to be eliminated in the future, the information collected is of high value because it represents the current state of knowledge, experiences, interests on MBR by multiple sectors, and represents a starting point to continue co-producing useful information for other sectors that did not participate, but that can be integrated in the future.

In this study, the categories environmental quality and economic value were frequently associated with meaningful places selected in this study; this can likely be explained that living in a natural protected area (Man and the Bioshpere program) (https://www.unesco.org/en/mab) where the primary objective is the conservation of biological diversity, as well as the improvement of relations between people and their environment through the implementation of environmental protection and management programs, scientific research and monitoring (CONANP, 2006). The category environmental quality was mainly mentioned by the government agency (CONANP) which is responsible for the management of the BRM. The local communities associated the economic and subsistence categories with the meaningful places, because they develop in conjunction with the government agency activities linked to the provision of local goods and services linked to environmental protection activities. Learning was the next most frequently mentioned category of meaningful places, this can be explained that scientists and non-governmental agency mainly conduct research activities or resource conservation programs (soil and vegetation) (Reyes Gomez et al., 2021).

The methodological approach of this chapter allowed the integration of biophysical and socio-economic variables in vector format; hence, the novelty of our study is that non-spatially meaningful socioeconomic variables that are not georeferrenced (for use in GIS) at local and regional scale were spatially captured by stakeholder mapping of meaningful places, when assigning diverse value to land. The full integration of stakeholder generated information and publicly available information of different thematic layers allows the delineation of a new social-ecological boundary of shared land. The novelty of this approach is that it considers a participatory diverse multidimensional value-based consideration of land and that it captures the collective interest of land. Therefore, the participatory action-oriented delimitation intends to establish new entry points for alternative multi-stakeholder land management (O'Sullivan et al., 2018), land governance (Essimi and Gaarde, 2024), and land planning approaches for the BRM (Castaneda, 2024). However, this type of delineation is by nature highly adaptive, dynamic and flexible in the sense that it is subject to updating and re-evaluation, because it is based on the perception, intuition, experience, interest, knowledge and judgment of different stakeholder groups highly experienced and knowledgeable about the local and current environmental conditions (Gatersleben et al., 2020; Knaps et al., 2022).

Since participatory mapping generates maps that reflect human perceptions (Müller et al., 2020), these may vary among social actors and individuals (Gatersleben et al., 2020). Hence, the boundaries proposed by the suggested methodological framework may not correspond to the mental maps of space constructed by individual social actors (Martín-López et al., 2017). However, they represent a shared space that represents a collective valuation, i. e. a space that connects to the roots of their cultural identiy, social networks, as well as to opportunities of innovative socioeconomic development and participatory research. It opens space to deepen and strengthen pertenency and care (Liebenberg et al., 2019).

We propose an alternative second spatial delineation representing the maximum spatial extent of the OPSE; it includes areas of socio-economic and biocultural relevance for the multi-stakeholder group of the study area. As in the core delineation of the boundary of the OPSE, the outer limit should be treated as flexible, dynamic and adaptable and subject to potential re-evaluation considering emerging economic, social or environmental factors (Piao et al., 2024). Since the OPSE's objective is to foster the co-generation of useful knowledge, implement environmental governance, i.e. joint planning of land use, joint water resource management and/or joint project development to represent shared interests, among others, more participatory mapping exercises are needed to expand and enrich the information generated so far.

We identified different social-ecological units based on the overlap of the thematic maps of hydrology, relief and land use/vegetation cover and meaningful places (through participatory mapping with GIS techniques). The utility of this SEU is that that can guide to a better use of resources by identifying and recognizing local knowledge and practices, that allow adjustment to socio-environmental conditions in a changing world (Piao et al., 2024). One of the advantages of the methodology is that the layers that stakeholder groups considered most important can be used. Therefore, the number of social-ecological units that emerge strongly depends on the thematic layers used and the different attributes cthat each thematic layer contains.

Several efforts have been made to determine and characterize social-ecological units. Hanspach et al. (2016) identified different social-ecological units that represent different types of villages with distinct species diversity patterns. Martin-López et al. (2017) identified social-ecological units trough the integration of the borders of ecodistricts and socio-economic units and determined the SES bound boundaries for each site of study. We validated the identification of social-ecological units with each stakeholder group. When socializing the results, the information contained in each SEU (geomorphology, watershed, vegetation, and categories of significant places) was explained to and discussed with the participants. Participants of the government sector and local communities expressed that these units become useful in case problems existed such that they could be identified and tackled collaboratively. Also, SEU could be monitored more easily rather than the whole extent of an OPSE; this would permit updating information of joint interest (fauna, geology, soils, rangeland health, etc.) of all stakeholders of an OPSE. In addition, the SEU presented here could be used to generate new approaches to co-design, co-generate projects, programs and policies for the decision making process at the OPSE context. To our knowledge, this is the first time that mapping meaningful places has been used to co-define the delineation of the boundaries of a social-ecological system and to generate socio-ecological units at a regional scale.

2.6 Conclusions

We have developed a methodology to collectively present the diverse values and need for care of shared land of a social-ecological system by mapping meaningful places considering multi-stakeholder perspectives. This method allowed collecting spatial data at diverse scales (regional or local), mainly of social, economic and cultural variables, which are not available in vector format at scales as small as ejidos (Mexican communal land tenure system). These data reflect the valuation, perception, intuition, experience, interest, knowledge, and inherent judgment of different stakeholder groups highly experienced and knowledgeable about the local and current environmental conditions. The approach builds on a deep understanding of invisible and often intangible associations people hold for places and thereby differs from those mapping exercises that combine separate social and biophysical data to identify social–ecological systems. The approach presented here may be a practical methodology, which can be implemented to identify similarities and discrepancies in the location of meaningful places and thereby to delineate more meaningful boundaries of a social-ecological system linked to an OPSE representing spatial identity of place by a group of coinciding stakeholders. Of course, the full complexity of social–ecological systems can never be captured by static maps or boundaries, however it increases the level of association and belonging to place. Downscaling this integrative mapping approach results in the co-definition of Social-Ecologcial Units, with potentially direct meaningful policy and decision-making relevance for sustainable resource management and thereby enhance the care for shared land.

We hope that the proposed approach will lead to broad adoption in SES analyses; we furthermore invite contributors to refine and expand upon our work. While our method provides an aproximation towards defining socio-ecological units for SES analyses, each application will need to parameterize the processing steps to align with the objectives of their respective research. We suggest that this presents a practical and meaningful approach which could be implemented in other countries and regions.

2.7 References

Alessa, L.N., Kliskey, A.A., Brown, G., 2008. Social-ecological hotspots mapping: a spatial approach for identifying coupled social-ecological space. Landscape Urban Plann. 85, 27–39, https://doi.org/10.1016/j.landurbplan.2007.09.007.

Altman, I., Low, S. M., 1992. Place attachment (Vol. 12). New York.

Berkes, F., Folke, C., 1998. Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience. Cambridge University Press.

Bengston, D.N., 1994. Changing forest values and ecosystem management. Soc. Nat. Resour. 7, 515–533.

Biggs, R., Clements, H., de Vos, A., Folke, C., Manyani, A., Maciejewski, K., Martín-López, B., Preiser, R., Selomane, O., and Schlüter, M. 2021. What are social-ecological systems and social- ecological systems research? In: Biggs, R., de Vos, A., Preiser, R., Clements, H., Maciejewski, K., Schlüter, M. 2021. The Routledge handbook of research methods for social-ecological systems. Taylor and Francis Group. Available online: https://library.oapen.org/handle/20.500.12657/49560

Bourgeron, P., Kliskey, A., Alessa, L., Loescher, H., Krauze, K., Virapongse, A., Griffith D., 2018. Understanding large-scale, complex, human–environmental processes: a framework for social–ecological observatories. Front Ecol Environ 16(S1): S52–S66. https://doi:10.1002/fee.1797

Botzata, A., Fischera, L. K., Kowarika, I. 2016. Unexploited opportunities in understanding liveable and biodiverse cities. A review on urban biodiversity perception and valuation. Global Environmental Change 39, 220–233. http://dx.doi.org/10.1016/j.gloenvcha.2016.04.008

Brouwer, H. and Woodhill, J., with Hemmati, M., Verhoosel, K. and van Vugt, S., 2016. The MSP Guide, How to design and facilitate multi-stakeholder partnerships, Wageningen: Wageningen University and Research, WCDI, and Rugby, UK: Practical Action Publishing, http://dx.doi.org/10.3362/9781780446691

Brown, G., Reed, P., 2000. Validation of a forest values typology for use in national forest planning. For Sci 46(2):240–247

Brunckhorst, D., Coop, P., Reeve, I., 2006. 'Eco-civic' optimisation: a nested framework for planning and managing landscapes. Landscape Urban Plann. 75, 265–281. https://doi.org/10.1016/j.landurbplan.2005.04.001

Castaneda, C. X. 2024. From Land Degradation to Habitat Loss: A Qualitative Assessment of Vegetation Cover in Protected Areas of Arid Lands. In: Weber, J., Sultana, S. (eds) The Changing Geography of National Parks and Protected Areas. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-031-74653-6_3

Castellarini, F., Siebe, C., Lazos, E., de la Tejera, B., Cotler, H., Pacheco, C., Boege, E., Moreno, A. R., Saldívar, A., Larrazábal, A., Galán, C., Casado, J. M., Balvanera, P., 2014. A social-ecological spatial framework for policy design towards sustainability: Mexico as a study case. Investigación Ambiental 6, 45–59. Available in: https://www.aacademica.org/eckart.boege/16.

Cerveny, L. K., Biedenweg, K., McLain, R., 2017. Mapping Meaningful Places on Washington's Olympic Peninsula: Toward a Deeper Understanding of Landscape Values. Environmental Management 60, 643–664. https://doi.org/10.1007/s00267-017-0900-x.

Chapin F. S. III, Knapp, C. N. 2015. Sense of place: A process for identifying and negotiating potentially contested visions of sustainability. Environmental science & policy 53, 38-46. http://dx.doi.org/10.1016/j.envsci.2015.04.012.

Choudhary, K., Boori, M. S., Kupriyanov, A., 2018. Spatial Modelling for Natural and Environmental Vulnerability through Remote Sensing and Gis in Astrakhan, Russia. The Egyptian Journal of Remote Sensing and Space Science, 21 (2), 139-147. https://doi.org/https://doi.org/10.1016/j.ejrs.2017.05.003.

Clermont, H. J. K., Dale, A., Reed, M. G., King, L., 2019. Sense of place as a source of tension in Canada's West Coast energy conflicts. Coastal Management 47(2):189-206. https://doi.org/10.1080/08920753.2019.1564953.

Colding, J., Barthel, S., 2019. Exploring the social-ecological systems discourse 20 years later. Ecology and Society 24 (1): 2. https://doi.org/10.5751/ES-10598-240102.

CONANP., 2006. Comisión Nacional de Áreas Naturales Protegidas. Programa de Conservación y Manejo de Reserva de la Biosfera de Mapimí, México. D. F. Available in: https://simec.conanp.gob.mx/pdf_libro_pm/139_libro_pm.pdf

Delhoume, J. P., 1992. Le milieu physique. In: Delhoume JP, Maury ME (eds) Actas Del Seminario Mapimí. Estudio de Las Relaciones Agua-Suelo-Vegetación En Una Zona Árida Del Norte de México Orientado a La Utilización Racional de Estos Recursos Para La Ganadería Extensiva de Bovinos. Instituto de Ecología, A.C., Instituto Frances de Investigaciones Científicas para el Desarrollo en Cooperación (ORSTOM). Centro de Estudios Mexicanos y Centroamericanos, Coyoacán, p 396.

Deng, Z. Y., Cao, J. S., 2023. Incorporating Ecosystem Services into Functional Zoning and Adaptive Management of Natural Protected Areas as Case Study of the Shennongjia Region in China. Scientific Reports, 13 (1), 18870. https://doi.org/10.1038/s41598-023-46182-0

Duggan, J., Cvitanovic, C., van Putten, I., 2024. An Evolving Understanding of Sense of Place in Social-Ecological Systems Research and the Barriers and Enablers to its Measurement, Environmental Management 73:19–33. https://doi.org/10.1007/s00267-023-01882-1.

Ellis, E. C., Ramankutty, N., 2008. Putting People in the Map: Anthropogenic Biomes of the World. Frontiers in Ecology and the Environment, 6(8), 439-447. https://doi.org/https://doi.org/10.1890/070062.

Elsawah, S., Filatova, T., Jakeman, A. J., Kettner, A. J., Zellner, M. L., Athanasiadis, I. N., Hamilton, S. H., Axtell, R. L., Brown, D. G., Gilligan, J. M., Janssen, M. A., Robinson, D. T., Rozenberg, J., Ullah, I. I. T., Lade, S. J., 2020. Eight grand challenges in socio-environmental systems modeling. Socio-Environmental Systems Modelling, vol. 2, 16226. http://dx.doi:10.18174/sesmo.2020a16226.

Essimi, B. A. C., Gaarde, I. 2024. Promoting inclusive land governance through multi-stakeholder platforms for successful land policy reforms in Africa. African Journal on Land Policy and Geospatial Sciences, 7 (1). DOI: https://doi.org/10.48346/IMIST.PRSM/ajlp-gs.v7i1.45924

Feng, X., Koch, J., 2024. Combining Vector and Raster Data in Regionalization: A Unified Framework for Delineating Spatial Unit Boundaries for Socio-Environmental Systems Analyses. International Journal of Applied Earth

Observation and Geoinformation, 128, 103745. https://doi.org/https://doi.org/10.1016/j.jag.2024.103745.

Fischer, J., Gardner, T. A., Bennett, E. M., Balvanera, P., Biggs, R., Carpenter, S., Daw, T., Folke, C., Hill, R., Hughes, T. P., Luthe, T., Maass, M., Meacham, M., Norström, A. V., Peterson, G., Queiroz, C., Seppelt, R., Spierenburg, M., Tenhunen, J., 2015. Advancing Sustainability through Mainstreaming a Social–Ecological Systems Perspective. Current Opinion in Environmental Sustainability, 14, 144-149. https://doi.org/https://doi.org/10.1016/j.cosust.2015.06.002.

Garcia, A., 2002. Vascular plants of the Mapimí biosphere reserve, México: a checklist. SIDA, Contributions to Botany, 20 (2), 797–807. http://www.jstor.org/stable/41968091.

García, G. A., Ferman, A. J. L., Arredondo, G. M. C., Galindo, B. L. A., Seingier, G., 2005. Modelo de planeación ambiental de la zona costera a partir de indicadores ambientales Sapiens. Revista Universitaria de Investigación, vol. 6, núm. 2, julio-diciembre, pp. 09-23. Universidad Pedagógica Experimental Libertador Caracas, Venezuela

Gatersleben, B., Wylesa, K. L., Myers, A., Opitza, B., 2020. Why are places so special? Uncovering how our brain reacts to meaningful places. Landscape and Urban Planning 197, 103758, https://doi.org/10.1016/j.landurbplan.2020.103758.

FELT. 2021. Felt: The only cloud-native GIS platform. Real-time collaborative maps. Accessed April 2022. Available at: https://felt.com/

Gottwald, S., and Stedman, R. C., 2020. Preserving ones meaningful place or not? Understanding environmental stewardship behaviour in river landscapes. Landscape and Urban Planning 198:103778. https://doi.org/10.1016/j.landurbplan.2020.103778

Grünberger O, Reyes-Gomez V, Janeau JL (eds), 2004. Las playas del desierto chihuahuense (parte Mexicana). Available in: https://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers15-11/010035079.pdf.

Halffter, G., 1984. Reservas de la biosfera: Conservación de la naturaleza para el hombre. Acta Zoológica Mexicana, 5: 4-48. Available in: https://azm.ojs.inecol.mx/index.php/azm/article/view/1926/2040

Hamann, M., Biggs, R., Reyers, B., 2015. Mapping social-ecological systems: identifying ‘green-loop’ and ‘red-loop’ dynamics based on characteristic bundles of ecosystem service use. Global Environmental Change 34, 218–226, https://doi.org/10.1016/j.gloenvcha.2015.07.008.

Hanspach, J., Loos, J., Dorresteijn, I., Abson, D. J., Fischer, J., 2016. Characterizing Social–Ecological Units to Inform Biodiversity Conservation in Cultural

Landscapes. Diversity and Distributions, 22 (8), 853-864. https://doi.org/https://doi.org/10.1111/ddi.12449.
Hernández, L., 2001. Historia Ambiental de la ganadería en México. Instituto de Ecología, A. C. Xalapa, Veracruz, México. 276 p.
Herrero, J. C., Arnaiz-Schmitz, C., Reyes, M. F., Telesnicki, M., Agramonte, I., Easdale, M. H., Schmitz, M. F., Aguiar, M., Gómez-Sal, A., Montes, C., 2018. What Do We Talk About When We Talk About Social-Ecological Systems? A Literature Review. Sustainability, 10 (8), 2950. https://doi.org/10.3390/su10082950.
Huber-Sannwald, E., Martínez, T. N., Espejel, I., Lucatello, S., Coppock, D. L. & Reyes Gómez, V. M., 2020. Introduction: International Network for the Sustainability of Drylands. Trasndisciplinary and Participatory Research for Dryland Stewardship and Sustainable Development. In: Huber-Sannwald, E., Martínez, T. N., Espejel, I. Lucatello, S., Coppock, D. L. & Reyes Gómez, V. (eds.) Stewardship of Future Drylands and Climate Change in the Global South. pp. 1-24. Springer International Publishing, India. https://doi.org/10.1007/978-3-030-22464-6.
Hummon, D. M. 1992. Community attachment. Pages 253-278 in I. Altman, and S. M. Low, editors. Place attachment. Human behaviour and environment, volume 12. Springer, Boston, Massachusetts, USA. https://doi.org/10.1007/978-1-4684-8753-4_12.
INEGI, 2018. (Instituto Nacional de Estadística y Geografía. Cartas temáticas. Accessed 15 April 2023 Available in: https://www.inegi.org.mx/temas/.
INEGI, 2024. Sociodemographic information at different scales. Accessed 20 April 2023. Available in: https://www.inegi.org.mx/temas/.
Knaps, F., S. Gottwald, C. A., Herrmann, S., 2022. Using meaningful places as an indicator for sense of place in the management of social-ecological systems. Ecology and Society 27(4): 9. https://doi.org/10.5751/ES-13340-270409.
Korpela, K. M., 1992. Adolescents' favourite places and environmental self-regulation. Journal of Environmental Psychology, 12(3), 249–258. https://doi.org/10.1016/S0272-4944(05)80139-2.
Kumar, P., Fürst, C., Joshi, P. K., 2021. Socio-Ecological Systems (SESs)—Identification and Spatial Mapping in the Central Himalaya. Sustainability, 13, 7525, https://doi.org/10.3390/su13147525.
Lauterio, M. C. L., Huber-Sannwald, E., Hernández, V. S. D., Leyva, A. J. C., Lucatello, S., Martínez, T. N., Mata, P. R. I., Reyes, G. V. M., Seingier, G., 2021. Métodos colectivos para tejer el camino desde la desertificación al desarrollo sostenible: los Observatorios Participativos Socio-Ecológicos. Ecosistemas 30 (3): 2232. https://doi.org/10.7818/ECOS.2232.

Lazzari, N., Becerro, M. A., Sanabria-Fernandez, J. A., Martín-López, B., 2019. Spatial Characterization of Coastal Marine Social-Ecological Systems: Insights for Integrated Management. Environmental Science & Policy, 92, 56-65. https://doi.org/https://doi.org/10.1016/j.envsci.2018.11.003.

Liebenberg, L., Wall, D., Wood, M., & Hutt-MacLeod, D. (2019). Spaces & Places: Understanding Sense of Belonging and Cultural Engagement Among Indigenous Youth. International Journal of Qualitative Methods, 18. https://doi.org/10.1177/1609406919840547

Li, H., Guan, Q., Fan, Y., Guan, C., 2024. Ecosystem Service Value Assessment of the Yellow River Delta Based on Satellite Remote Sensing Data. Land, 13, 276. https://doi.org/10.3390/land13030276.

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., Pell, A. N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C. L., Schneider, S. H., Taylor, W. W., 2007. Complexity of Coupled Human and Natural Systems. Science, 317 (5844), 1513-1516. https://doi.org/10.1126/science.1144004.

López, R. S., Lenny G. J. van Bussel L. G. J., Alkemade, R., 2024. Classification of agricultural land management systems for global modeling of biodiversity and ecosystem services. Agriculture, Ecosystems and Environment 360, 08795. https://doi.org/10.1016/j.agee.2023.108795.

Martínez-Harms, M. J., Quijas, S., Merenlender, A. M., Balvanera, P., 2016. Enhancing Ecosystem Services Maps Combining Field and Environmental Data. Ecosystem Services, 22, 32-40. https://doi.org/https://doi.org/10.1016/j.ecoser.2016.09.007.

Martínez, T. N., Huber-Sannwald, E., Mata, P. R. I., Reyes, G. V. M., Villarreal, W. C., Cázares, R. R., Urquidi, M. J., López, P. J. J., 2020. Chapter 10 Conservation and Development in the Biosphere Reserve of Mapimí: A Transdisciplinary and Participatory Project to Understand Climate Change Adaptation. In: Huber-Sannwald, E., Martínez, T. N., Espejel, I. Lucatello, S., Coppock, D. L. & Reyes Gómez, V. (eds.) Stewardship of Future Drylands and Climate Change in the Global South. pp. 1-24. Springer International Publishing, India. https://doi.org/10.1007/978-3-030-22464-6.

Martínez, T. N., Torres, L.A., 2013. Arqueología Comcáac: El Paisaje Cultural a través del tiempo. Creel, paper presented at 1er Congreso Internacional CarlLumholtz. culturas, geografías y temporalidades", Los nortes de México.

Martínez, T. N., Torres, C. L. A. 2018. Walking the desert, paddling the sea: Comcaac mobility in time. Journal of Anthropological Archaeology 49, 146–160. https://doi.org/10.1016/j.jaa.2017.12.004.

Martín-Lopez, B., Palomo, I., García L. M., Iniesta A. I., Castroe, A. J., García Del Amo, D., Gómez B. E., Montes, C., 2017. Delineating boundaries of social-

ecological systems for landscape planning: A comprehensive spatial approach. Land Use Policy 66, 90–104. http://dx.doi.org/10.1016/j.landusepol.2017.04.040.
McCrory, G., Schäpke, N., Holmén, J., Holmberg, J., 2020. Sustainability-oriented labs in real-world contexts: An exploratory review. Journal of Cleaner Production 277, 123202. https://doi.org/10.1016/j.jclepro.2020.123202.
Minet, J., Curnel, Y., Gobin, A., Goffart, J-P., Mélard, F., Tychon, B., Wellens, J., Defourny, P., 2017. Crowdsourcing for agricultural applications: A review of uses and opportunities for a farmsourcing approach. Computers and Electronics in Agriculture 142, 126–138. http://dx.doi.org/10.1016/j.compag.2017.08.026.
Müller, S., Backhaus, N., Buchecker, M., 2020. Mapping meaningful places: A tool for participatory siting of wind turbines in Switzerland? Energy Research & Social Science 69, 101573. https://doi.org/10.1016/j.erss.2020.101573.
Naidoo, R., Balmford, A., Costanza, R., Fisher, B., Green, R. E., Lehner, B., Malcolm, T. R., Ricketts, T. H., 2008. Global Mapping of Ecosystem Services and Conservation Priorities. Proceedings of the National Academy of Sciences, 105 (28), 9495-9500. https://doi.org/10.1073/pnas.0707823105.
Niu, H., Silva, E. A., 2020. Crowdsourced Data Mining for Urban Activity: Review of Data Sources, Applications, and Methods. Journal of Urban Planning and Development, 146 (2), 04020007. https://doi.org/10.1061/(ASCE)UP.1943-5444.0000566.
Ostrom, E., 2009. A General Framework for Analyzing Sustainability of Social-Ecological Systems. Science, 325 (5939), 419-422. https://doi.org/10.1126/science.1172133.
O’Sullivan, L., Wall, D., Creamer, R. et al. 2018. Functional Land Management: Bridging the Think-Do-Gap using a multi-stakeholder science policy interface. Ambio 47, 216–230. https://doi.org/10.1007/s13280-017-0983-x
Pascual, U., Palomo, I., Adams, W. M., Chan, K. M. A., Daw, T. M., Garmendia, E., Gómez-Baggethun, E., de Groot, R. S., Mace, G. M., Martín-López, B., Phelps, J., 2017. Off-Stage Ecosystem Service Burdens: A Blind Spot for Global Sustainability. Environmental Research Letters, 12 (7), 075001. https://doi.org/10.1088/1748-9326/aa7392.
Piao, S. et al. 2024. Socioeconomic and Environmental Changes in Global Drylands. In: Fu, B., Stafford-Smith, M. (eds) Dryland Social-Ecological Systems in Changing Environments. Springer, Singapore. https://doi.org/10.1007/978-981-99-9375-8_6
Priego, S. A., Bocco, G., Mendoza, M., Garrido, A., 2010. Propuesta para la generación semiautomatizada de unidades de paisajes. Fundamentos y Métodos. Instituto Nacional de Ecología, Centro de Investigaciones en

Geografía Ambiental, Morelia, Michoacán, México. Available at: https://www.ciga.unam.mx/publicaciones/images/abook_file/propuestaSemi.pdf.

Proshansky, H. M., Fabian, A. K., Kaminoff, R., 1983. Place-identity: Physical world socialization of the self. Journal of Environmental Psychology, 3(1), 57–83.

Qu, Y., Lu, M., 2018. Identifying conservation priorities and management strategies based on ecosystem services to improve urban sustainability in Harbin, China. PeerJ 6:e4597. https://doi.org/10.7717/peerj.4597.

Reyes, G. V. M., Huber-Sannwald, E., Martínez, T. N., Espejel, C. I., Lucatello, S., Bowker, M. A., Lauterio, M. C. L., 2021. Long-Term Socio-Ecological Research in the Biosphere Reserve in Mapimi, Mexico: A Multidimensional Participatory Observatory of Rangeland. Pastoral Systems International Grassland Congress Proceedings. Available in: https://uknowledge.uky.edu/cgi/viewcontent.cgi?article=4343&context=igc.

Rocha, J., Malmborg, K., Gordon, L., Brauman, K., DeClerck, F., 2020. Mapping socialecological systems archetypes. Environmental Research Letters. 15 (3), 034017. https://doi.org/10.1088/1748-9326/ab666e.

Ropero, R. F., Maldonado, A. D., Uusitalo, L., Salmerón, A., Rumí, R. and Aguilera, P. A., 2021. A Soft Clustering Approach to Detect Socio-Ecological Landscape Boundaries Using Bayesian Networks, Agronomy 11, no. 4: 740. https://doi.org/10.3390/agronomy11040740.

Sinare, H., Gordon, L. J., Enfors Kautsky, E., 2016. Assessment of ecosystem services and benefits in village landscapes – a case study from Burkina Faso. Ecosystem Services 21, 141–152, https://doi.org/10.1016/j.ecoser.2016.08.004.

Schermerhorn, J.R., Hunt, J., Osborn, R.N., 2000. Organizational Behaviour. Wiley and Sons, New York.

SMN (Servicio Meteorológico Nacional), 2024. Normales climatológicas del estado de Durango. Accessed 10 July 2022. Available in: https://smn.conagua.gob.mx/tools/RESOURCES/Normales_Climatologicas/Mensuales/dgo/mes10165.txt.

Spiridonov, A.I., 1981. Principios de la metodología de las investigaciones de campo y el mapeo geomorfológico. Facultad de Geografía de la Universidad de La Habana. Editorial MES, Ciudad de la Habana, Cuba.

Sterk, M., A van de Leemput, I., THM Peeters, E., 2017. How to conceptualize and operationalize resilience in socio-ecological systems? Current Opinion in Environmental Sustainability 28:108–113. http://dx.doi.org/10.1016/j.cosust.2017.09.003.

Stoffelen, A., Kamminga, O., Groote, P., Meijles, E., Weitkamp, G., Hoving, A., 2024. Making use of sense of place in amalgamated municipalities. Regional and federal studies. 34 (4), 521–543. https://doi.org/10.1080/13597566.2022.2161526.

Stokowski, P. A., 2008. Creating social senses of place: new directions for sense of place research in natural resource management. Pages 31-60 in L. E. Kruger, T. E. Hall, and M. C. Stiefel, editors. Understanding concepts of place in recreation research and management. U.S. Forest Service, Pacific Northwest Research Station, Portland, Oregon, USA.

Toledo, V. M., 2005. Repensar la conservación: ¿áreas naturales protegidas o estrategia bioregional? Gaceta Ecol 77:67–83. Available at: https://www.redalyc.org/pdf/539/53907705.pdf.

USGS, 2018. Unisted States Geological Survey, USGS EROS Archive - Digital Elevation - Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global. Accessed 25 July 2023. Available at: https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-shuttle-radar-topography-mission-srtm-1?qt-science_center_objects=0#qt-science_center_objects.

USGS, 2022. United States Geological Survey, Digital elevation model. Accessed 25 July 2023. Available in https://earthexplorer.usgs.gov/.

Václavík, T., Lautenbach, S., Kuemmerle, T., Seppelt, R., 2013. Mapping Global Land System Archetypes. Global Environmental Change, 23 (6), 1637-1647. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2013.09.004.

Verbrugge, L., Buchecker, M., Garcia, X., Gottwald, S., Müller, S., Præstholm, S., Olafsson, A. S., 2019. Integrating sense of place in planning and management of multifunctional river landscapes: experiences from five European case studies. Sustainability Science 14 (3): 669-680. https://doi.org/10.1007/s11625-019-00686-9.

Yang, X., Liu, S., Jia, C., Liu, Y., Yu, C., 2021. Vulnerability Assessment and Management Planning for the Ecological Environment in Urban Wetlands. Journal of Environmental Management, 298, 113540. https://doi.org/https://doi.org/10.1016/j.jenvman.2021.113540.

Yang, Y., Bao, W., de Sherbinin, A., 2023. Mapping Fine-Resolution Nested Social-Ecological System Archetypes to Reveal Archetypical Human-Environmental Interactions. Landscape and Urban Planning, 239, 104863. https://doi.org/https://doi.org/10.1016/j.landurbplan.2023.104863

Chapter 3

---

3. Performance Evaluation of Global Precipitation Datasets in Northern Mexico Drylands

3.1 Abstract

Precipitation is a fundamental process in the hydrological cycle; hence reliable and accurate information on the spatiotemporal rainfall distribution is critical for climate change modelling, local decision-making, and the development of climate adaptation policies. In Mexico's drylands, the rainfall gauge network is highly heterogeneously distributed and frequently with incomplete datasets. Here, we examine how this deficient rainfall information can be best compensated by information derived from global precipitation datasets. We applied a performance evaluation of CHIRPS, CFS-2, AgERA5, PERSIANN-CDR and TerraClimate and compared this data with observed monthly precipitation records (1983-2018) for dryland regions associated with a network of Participatory Social-Ecological Observatories including Mediterranean climate in NW-Mexico, coastal arid climate in the Sonora Desert, and semiarid climate in the Chihuahua Desert. We compared monthly and annual rainfall of the global datasets with observed data with the Pearson's Correlation Coefficient, means, standard deviations, Root Mean Square Errors and Taylor diagrams. The results indicate that CHIRPS and AgERA5 can reproduce the precipitation cycle at monthly and annual scales; also, the inter-annual variability is well captured. Our results suggest that for Mexican drylands, global precipitation datasets can be used

to understand drought patterns, for hydrological modeling, for local decision-making, and for the development of urgently needed climate adaptation policies.

KEYWORDS: Climate records, Data quality control, Databases, Climate variability, Decision making, Time series

3.2 Introduction

In drylands, precipitation is a fundamental process in the hydrological cycle; hence, reliable and accurate information on its spatiotemporal distribution plays a vital role in many scientific studies and operational applications (Fernandez et al., 2022), especially in climatology and regional meteorology (Rincón-Avalos et al., 2022). The access to reliable precipitation information is also critically important for local farmer and agricultural communities, as their livelihoods directly depend on the availability and access to freshwater (Dorward et al., 2015). Precipitation at a given location is usually measured with rain gauges, disdrometers, and radars; rain gauges are the most commonly used devices for directly determining point precipitation at a given surface by measuring the depth of rainfall as it accumulates over time (Sun et al., 2018). These observations are most frequently used at the local scale; they are considered the most direct and accurate precipitation data sources (Fernandez et al., 2022). In Mexican territory, precipitation observations and recording are made manually, causing a delay in the availability of this information for use in climatological and hydrological studies (Velázquez and Talledos-Sánchez, 2019). Also, the distribution of rain gauges is neither homogeneous nor spatially representative (Rincón-Avalos et al., 2022). This is problematic when needing to quantify the annual precipitation fallen at a given location, particularly for local decision-makers, such as farmers.

Drylands exhibit an inherently high spatial heterogeneity of precipitation; besides, this is where rainfall is highly unpredictable, sporadic, and increasingly extreme, such that it can vary greatly within 1 or 2 km. Hence, there is a multifaceted need for increased accuracy of rainfall information at the appropriate spatial scale. Precise quantitative estimates of precipitation for a given dryland region are essential for water resource management, rain-fed agriculture, studies of climate trends and variability, and hydrological forecasting (Jiang et al., 2012; Xu et al., 2017). To respond to this call for information, gridded precipitation data can be obtained from three alternative sources: gauge-based products, reanalysis products, and satellite-based products (Song et al., 2022).

The generation of gridded precipitation products is based on long-term mostly automated rain gauge observations collected by National Weather Services. The procedure consists of assembling all global data points into one integrated global dataset (Sun et al., 2018) coordinated by global climatology centers [e.g., the Climate Research Unit (CRU); Harris et al., (2020), the Global Precipitation Climatology Centre (GPCC); Schneider et al., (2020)]. Reanalysis products refer to the merge of numerical forecast products and observational data that generate a synthesized estimate of the state of the system across a uniform grid, considering spatial homogeneity, temporal continuity, and a multidimensional hierarchy (Sun et al., 2018). Examples of reanalysis datasets currently in use in climate studies include the Climate Forecasting System Reanalysis (CFSR-2) (Saha et al., 2014), the Japanese 55-year Reanalysis (JRA-55) (Kobayashi et al., 2015), the Modern-Era Retrospective Analysis for Research and Applications (MERRA) and MERRA-2 (Reichle et al., 2017; Gelaro et al., 2017) and the fifth generation of the European Agrometeorological Reanalysis (AgERA5) (Boogaard et al., 2020).

Precipitation information derived from remote sensing is obtained from sensors on board of satellites; they are invaluable tools for automated global homogenous measurements of atmospheric parameters at regular temporal intervals (Sun et al., 2018; Song et al., 2022). Some examples of these datasets are the Climate Prediction Center Morphing Method (CMORPH) (Joyce et al., 2004), Tropical Rainfall Measuring Mission with the Multi-satellite Precipitation Analysis (TMPA) (Huffman et al., 2007), the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) (Funk et al. 2015a), the Integrated Multi-satellite Retrievals for the Global Precipitation Measurement (GPM) mission (IMERG) (Huffman et al., 2020), and the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Climate Data Record (PERSIANN-CDR) (Ashouri et al. 2015). Satellite-derived precipitation data and reanalysis products have been used for different applications around the world; they have been verified both globally and regionally (Prakash et al., 2019; Tan et al., 2020; Rachidi et al., 2023).

Drylands are the largest biome complex on Planet Earth and present an extraordinarily high biotic and cultural richness, which is under threat because of climatic change and human-induced activities (Huber-Sannwald et al., 2020).

Drylands cover 45.4% of the Earth's land surface (Prăvălie et al., 2019); in México, they occupy 64.8 % of the terrestrial area (SEMARNAT, 2018). Global drylands are projected to expand by 5% by the end of the century due to global warming (Liu et al., 2023); hence increased water shortages at the global level will strongly affect natural ecosystems and agricultural and farming practices. Therefore, long-term climatic monitoring at the local scale will become increasingly important.

Few studies have analyzed and evaluated the performance of global precipitation datasets for the Mexican territory, in particular for drylands. For instance, Miranda (2002) evaluated precipitation estimates for whole Mexico comparing the PERSIANN dataset and daily gauge data with daily records for June to October 2000. The results provided a reasonable approximation to the original rainfall data; however, a clear overestimation of precipitation was attributed to the inconsistency and quality of the observed data. Mayor et al. (2017) evaluated the precipitation product of the Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (IMERG) for central and northern Mexico for the period between April 2014 and October 2015. While IMERG was able to reproduce diurnal and daily cycles of average precipitation, rain gauge data were overestimated. Also, IMERG tends to improve the detection of precipitation and decrease the magnitude of error for regions at high elevations. Velázquez and Talledos (2018) compared observed meteorological data with two post-processed gridded datasets and one reanalyzed dataset for the simulation of mean and high streamflow in the Valles basin in central Mexico. The selected post-processed gridded datasets differed from the observed meteorological data, where the precipitation and temperature were generally underestimated and the annual cycle was not well represented. Recently, Rincón et al. (2022) evaluated the reliability of satellite and reanalysis precipitation products hosted by the Google Earth Engine (GEE) repository compared to national rain gauge observations for Mexico for 2001 - 2017. All products seemed to capture the general precipitation patterns at annual, seasonal, and monthly scales; however, the accuracy of the product at daily scale was clearly lower.

As observed, there is not a universally best performing precipitation product. Therefore, a process for validating gauge-based products, reanalysis products, and satellite-based derived information is required in a case study approach (Hinge et al., 2021). Even though there are a plethora of studies characterizing and quantifying precipitation datasets across the globe at distinct spatial and temporal scales, no study has yet comprehensively evaluated these global precipitation datasets for Mexican drylands, which cover over 60% of its terrestrial surface and include diverse climate regions (Mediterranean, arid and semiarid). The livelihoods of many local communities in Mexican drylands depend on rain-fed agriculture. Hence, knowledge on climate variability based on accurate meteorological records is essential for several reasons: decision making, as complementary information to local records and experience and as baseline for local climate monitoring.

The present study evaluates global precipitation products at regional scale and specifically considers a network of dryland systems associated with local Participatory Social-ecological Observatories (OPSE by its Spanish acronym) along a west-east transect reaching from the Mediterranean climate in NW Mexico, coastal arid climate in the Sonora Desert, and semiarid climate in the Chihuahua Desert in central and east Mexico. The OPSEs are living laboratories established to collect, exchange, and co-generate useful knowledge among different stakeholders and to facilitate the co-management of knowledge; they are innovation hubs for sustainable development in drylands (Martinez et al., 2021). For dryland areas lacking meteorological stations or with incomplete climate records, as applies for large areas in Mexico, the evaluation and potential use of precipitation databases (as an alternative to gauge data) is an underexplored opportunity for the identification, characterization, and projection of increasingly occurring extreme weather phenomena (Spinoni et al., 2020).

In this study, we address the following questions: (1) How do precipitation products perform in Mexican drylands considering different basin areas associated with the OPSE network? (2) How does data quality of each precipitation product at different temporal scales in the context of the OPSE? Hence, we compared and evaluated the performance of five precipitation datasets (CHIRPS, CFS-2, AgERA5, PERSSIANN-CDR and TerraClimate) in the Northern Mexico dryland regions, and assessed the reproducibility of these datasets considering monthly and annual rainfall cycles. The criteria for the selection of precipitation data sets were based on the finest horizontal resolution covering small basins within the OPSEs, and data availability for 1979 to present. We opted to examine these precipitation products as they are constantly updated such that these databases could potentially be considered for future climate monitoring efforts. We aimed at identifying the product that best reproduces the observed precipitation data and to validate their use for potential hydrological and climate studies in regions with scarce data such as the OPSEs.

3.3 Materials and Methods

3.3.1 Study área

The dryland regions and respective basins associated with the OPSEs lie between latitude 23–32° N and longitude 99-116 ° W (Fig. 3.1.) The OPSE Valle de Guadalupe (2380 km^2) is situated in NW Mexico; its main productive activity is viticulture. However, Viticulture in this region subsists in an environment of adversity, this industry exhibits four warning calls: (1) prolonged droughts; (2) overexploitation of groundwater, which is the main source of supply; (3) exploitation of sand of the stream Guadalupe thereby reducing the capacity of natural retention; and (4) the attempts to convert land to the tourist-habitational activity and of recreation (Santes and Camacho, 2018). The Mediterranean type climate exhibits clear seasonal and annual temperature and precipitation variability, with persistent dry periods during the summer months (Molina et al. 2016). Rainfall is generally intense during the winter months (56% of annual precipitation); mean annual precipitation ranges from 59 mm to 589 mm, with an average annual precipitation of 280 mm while the average annual temperature is 18.1 °C with a normal minimum of 12.7 °C in the month of December and a normal maximum of 25.2 °C in the month of August (SMN, 2024a).

The OPSE Mapimí is part of the Biosphere Reserve of Mapimí (BRM) located in the Chihuahuan Desert between latitude 26.1-26.6 ° N and longitude 103-104 ° W. In 1977, the BRM was decreed a UNESCO Man and the Biosphere (MAB) Reserve, marking the beginning of the biosphere reserve program in Mexico and Latin America (Halffter, 1984). Biosphere reserves are expected to promote conservation of the genetic diversity of species, research, environmental monitoring, training and education in management plans (Reyes et al. 2021). The climate weather is arid mostly with summer rainfall regime (July to September). The average annual rainfall is 256 mm, of which 54% correspond to the summer months and 9% to the winter months (December–February), the highest record is 600 mm and lowest is 81 mm of annual rainfall. The average annual temperature is 20.4 °C with a normal minimum of 11.4 °C in the month of January and a normal maximum of 27.3 °C in the month of June (SMN, 2024b). The vegetation is characterized by xerophytic scrub and halophytic grassland ecosystems (CONANP, 2006). The basins associated with this OPSE cover approximately 30,089 km2 (INEGI, 2023).

Finally, the El Tokio OPSE is located in NE Mexico, between latitude 23-25 ° N and longitude 100-101 ° W. This region is a priority conservation area in Mexico and North America, for its adjacent grassland ecosystem holds the world's last remaining colonies of the Mexican Black-tailed Prairie Dog (Cynomys mexicanus) and serves as habitat for over 250 bird species and other rare, endemic, and endangered species of flora and fauna (Baez et al., 2018). This OPSE is characterized by a dry semi-arid climate, the annual rainfall varies between 336 mm and 785 mm with average annual precipitation is 492 mm, while the average annual temperature is 16 °C with a normal minimum of 1.9 °C in the month of January and a normal maximum of 29.2 °C in the month of June (Baez et al., 2018). The basins associated with the OPSE El Tokio cover approximately 28,671 km2 (INEGI, 2023). The main environmental problems in this region are the land use change for potato and alfalfa cultivation, inadequate livestock grazing, and soil salinization (CONABIO, 2023).

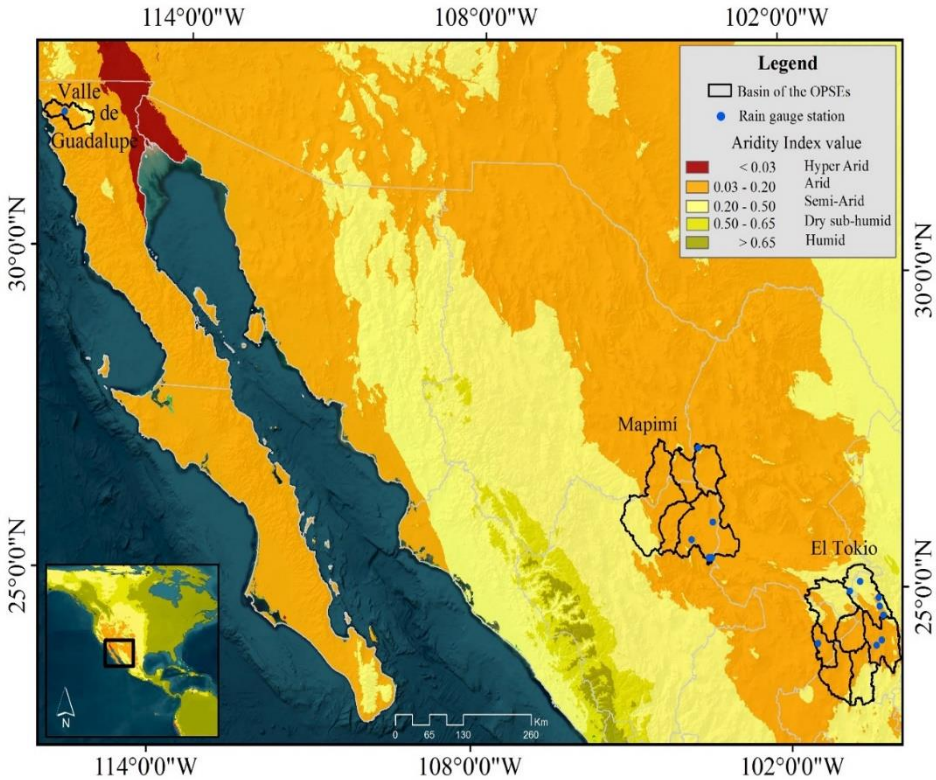


Fig. 3.1. Study area in the dryland region of Northern Mexico including the territories of the Social-Ecological Participatory Observatories (OPSE), a) Valle de Guadalupe, b) Mapimí Biosphere Reserve, and c) El Tokio grassland region and the spatial distribution of the aridity index (AI). The AI is a widely used measure of dryness of the climate at a given location (UNE, 1997).

3.3.2 Data and methods

3.3.2.1 Observed precipitation data

Monthly precipitation data were obtained from the National Meteorological Service (SMN by its Spanish acronym) using an application (developed to be used with

Google Earth) that displays Mexico's rain gauge stations for two categories: operating and suspended (SMN, 2024c). In the study area, a total of 102 stations were identified, of which 43 are suspended and 59 operating. The precipitation data were scrutinized to meet two basic criteria: 1) the stations count with at least 30 years of information, and 2) the time series do not present more than 10% missing information in their historical records; 23 stations met these criteria.

Gaps in the monthly precipitation time series were filled using the inverse distance weighting method (IDW), also known as the US National Weather Service method (ASCE, 1996). To validate the consistency and homogeneity of the data series, a graphical analysis, and three statistical homogeneity tests were performed: 1) the normal homogeneity test (SNHT) (Alexanderson and Moeberg, 1997), 2) the Pettitt method (Pettitt, 1979), and 3) the Buishand method (Buishand, 1982). The null hypothesis (Ho) for the three tests was that the data are homogeneously distributed ($\alpha = 0.05$). The tests were performed with the XLSTAT software. The selection of time series was as follows: if the time series were rejected by only one test, it was considered reliable; if the time series were rejected by two tests, the information was classified as moderately reliable; if the time series were rejected by all tests, the information was considered unreliable (Cerano et al., 2020). Following these criteria, only 14 meteorological stations had reliable time series data (Table 3.1) (Table 3.1S).

Table 3.1. Characteristics of selected rain gauge stations in Northern Mexico used in this study.

ID	Name of rain gauge station	OPSE	Latitude (°)	Longitude (°)	Altitude (m)	Mean annual	Years of

						rainfall (mm)	rainfall records
2001	Agua Caliente	Guadalupe	32.108	-116.545	400	223	1983-2018
5039	Sierra Mojada	Mapimí	27.286	-103.700	1256	356	1983-2018
10085	Tlahualilo	Mapimí	26.106	-103.443	1100	260	1983-2018
10045	Mapimi	Mapimí	25.832	-103.847	1388	348	1983-2018
10108	Cd Lerdo	Mapimí	25.546	-103.522	1140	262	1983-2018
5026	Coyote	Mapimí	25.542	-103.469	1223	222	1983-2018
19115	El Cuije	El Tokio	25.108	-100.663	1870	423	1983-2018
5136	Las Hormigas	El Tokio	24.960	-100.861	2110	386	1983-2018
19020	El Potosi	El Tokio	24.843	-100.321	1890	356	1983-2018
19182	San Roberto	El Tokio	24.710	-100.303	1888	367	1983-2018
19050	San Jose de Raíces	El Tokio	24.567	-100.238	1870	424	1983-2018
19059	Santa Rosa	El Tokio	24.173	-100.287	1664	366	1983-2018
32078	San Tiburcio	El Tokio	24.148	-101.484	1885	357	1983-2018
19138	Santa Ana	El Tokio	24.092	-100.388	1689	366	1983-2018

3.3.2.2 Gridded precipitation data

Five global precipitation datasets were used (Table 3.2). CHIRPS is a satellite-based precipitation product developed by the United States Geological Survey and the Climate Hazard, with a spatial resolution of 0.05˚ × 0.05˚ (~ 5.4 km); it covers 50˚ S to 50° N and 180° W to 180°E; its time series span from 1981 to 2023 (Funk et al., 2015a; 2015b). The precipitation product CFS-2 of the National Center for Environmental Prediction (NCEP) is an upgraded version of CFS-1 (Saha et al. 2010) nearly in all aspects of the data assimilation and forecast model components; CFS-2 has a horizontal resolution of 38 km (0.5° × 0.5°) and a 3D variational analysis scheme of the upper-air atmospheric state for 64 vertical levels (Saha et al., 2014). The AgERA5 dataset is based on the fifth-generation climate reanalysis dataset (ERA5) (Hersbach et al., 2020) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) and provides daily surface meteorological data for the period from 1979 to present as input for agriculture and agro-ecological studies; the dataset is updated every day and it is close to real-time (Boogaard et al., 2020).

The PERSIANN-CDR dataset is generated by the PERSIANN algorithm using gridded satellite infrared data (GridSat-BI). NCEP Stage IV radar data are used to train the Artificial Neural Networks model and create nonlinear regression parameters. The model prediction (precipitation estimates) is then calibrated using the monthly Global Precipitation Climatology Project (GPCP) version 2.2 product that contains precipitation gauge data generated by the GPCP mission in order to increase the reliability of the PER-SIANN-CDR data (Ashouri et al., 2015). TerraClimate is a dataset of high-spatial resolution (1/24°, ~4 km) generating monthly climate and climatic water balances for global terrestrial surfaces for the years 1958 to 2015. TerraClimate uses climatically aided interpolation, combining high spatial resolution climatological normals from the WorldClim dataset, with coarser resolution temporal (i.e., monthly) data from other sources, to produce a monthly datasets of precipitation, maximum and minimum temperature, wind speed, vapor pressure, and solar radiation (Abatzoglou et al., 2018).

Table 3.2. Introduction of five global precipitation datasets.

Dataset	Data source	Spatial resolution	Temporal coverage	Reference
CHIRPS V 2.0	Satellite, Gauge data	0.05°	1981-present	Funk et al. 2015a,b
CFS-2	Reanalysis	0.5°	1979-present	Saha et al. 2014
AgERA5	Reanalysis	0.1°	1979-present	Boogaard et al. 2020
PERSIANN CDR	Satellite - Artificial Neural Networks	0.25°	1983-present	Ashouri et al. 2015
TerraClimate	Interpolation	1/24°	1958-2021	Abatzoglou et al. 2018

3.3.2.3 Downloading of time series

We examined five sources of precipitation estimates (CHIRPS, CFS-2, AgERA5, PERSSIANN-CDR and TerraClimate) considering the years 1983 to 2018. The precipitation datasets were generated by two methods and analyzed for both local rain gauge stations and at basin level scale (Figure 3.2). Firstly, the PERSIANN-CDR, TerraClimate, and CHIRPS datasets were downloaded from their official repositories (Table 3.2) and processed with the Python 3 libraries, Numpy, and netCDF4. The gridded monthly precipitation datasets were built with the average precipitation in the cell centers within the spatial domain of each study basin. For the generation of precipitation time series per point, a minimum Euclidean distance algorithm was implemented to identify the closest grid center with respect to the location of each observed meteorological station. The CFS-2 and AgERA5 datasets were obtained using the Climate Engine (CE) platform (https://app.climateengine.com/climateEngine) (Huntington et al., 2017).

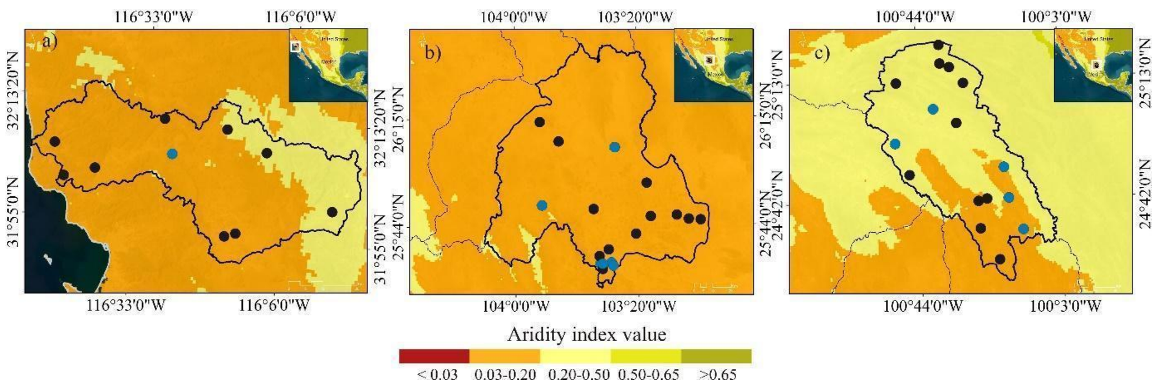


Fig. 3.2 Spatial distribution of the Aridity Index (AI) in the basins of a) Valle de Guadalupe (OPSE Guadalupe), b) Nazas-Santa Rosa (OPSE Mapimí), and c) San Rafael (OPSE El Tokio). Blue dots present the rain gauge stations selected for each basin. Black dots refer to the locations of weather stations that did not meet the selection criteria for this study.

3.3.2.4 Comparison of precipitation datasets

To compare the precipitation datasets against the observed precipitation for each weather station, four statistical measures were selected: Pearson's Correlation Coefficient (r), mean, standard deviation and Root Mean Square Error (RMSE). Taylor diagrams (Taylor, 2001) and graphical plots were generated to compare monthly rainfall time series and observed data at the basin scale. An estimation of the trend was performed using Sen's slope (Sen, 1968) a non-parametric technique for estimating linear trends, where no underlying distribution assumptions are made on the data (Tamm et al., 2023).

3.4 Results

3.4.1 Monthly precipitation cycle of rain gauge stations compared vs global precipitation datasets

Monthly mean precipitation of the rain gauge stations varied with respect to geographic region (Fig. 3.3). The 2001 station (Agua Caliente) is the only rain gauge with a Mediterranean winter rainfall regime with precipitation occurring between the beginning of November and the end of March (81 % of annual precipitation). TerraClimate captured monthly precipitation cycles most efficiently, followed by CHIRPS, and AgERA5. However, CHIRPS and AgERA5 overestimated while CFS-2 and PERSIANN-CDR underestimated precipitation for the winter months. All datasets overestimated summer precipitation, except for TerraClimate.

The other rain gauge stations used for this study have typical desert climate with summer rainfall from May to October. CFS-2 overestimated monthly precipitation in most rain gauge stations, mainly in the case of stations 10045 and 10108 located in OPSE Mapimí, and stations 19115, 19020 and 19182 located in OPSE El Tokio. These stations had the highest observed mean annual precipitation (348-420 mm) of all analyzed rain gauges. In the OPSE Mapimí, the observed precipitation occurred between July and September. The annual precipitation cycle by the datasets is maintained, however some precipitation products showed a consistent seasonality with the observed precipitation (Terra Climate, CHIRPS), while in other locations they overestimated or underestimated summer precipitation (CFS-2).

In the OPSE El Tokio, the distribution of precipitation is similar as in Mapimí, with the main precipitation season occurring between May and September. CFS-2 overestimated monthly precipitation in some stations, but in the 32078 rain gauge station the pattern of distribution compared with observed data showed good agreement. In general, the annual precipitation cycles were well represented for the precipitation datasets; however, the overestimation or underestimation with the observed data can be attributed to particular local conditions associated with the stations, like the topography (orographic effects).

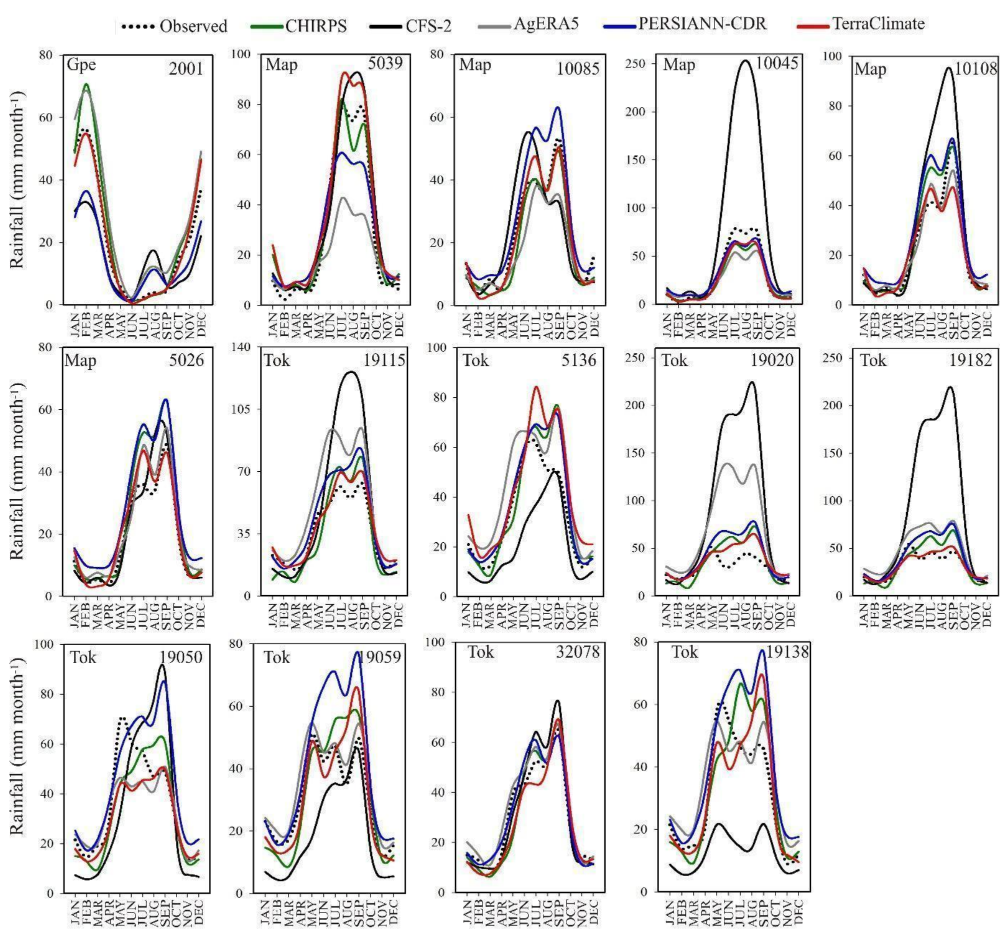


Fig. 3.3. Monthly mean precipitation (n=36 years) of selected rain gauge stations associated with three Social-Ecological Participatory Observatories (OPSEs) in three dryland regions of Northern Mexico occurring in Mediterranean (OPSE Guadalupe, Gpe) and semiarid desert climates (OPSE Mapimí, Map; and OPSE El Tokio, Tok). The station 2001 (OPSE Guadalupe) has a winter rainfall regime, while the other stations present summer rainfall regime. The sequence of listing stations corresponds to Table 3.1.

Considering the performance evaluation of the five datasets (Fig. 3.4), the statistics suggest that each dataset performance differs for selected rain gauge stations. Overall, precipitation products showed a good correlation with the observed monthly precipitation data, except for CFS-2. In the case of the OPSE Guadalupe, the best result was observed for AgERA5 followed by CHIRPS (r=0.94 and r=0.92, respectively). For the OPSE Mapimí, CHIRPS, PERSIANN-CDR, and TerraClimate had a significant correlation with the rain-gauge data (r= 0.80, r=0.78, and r=0.76, respectively). For the OPSE El Tokio, AgERA5, PERSIANN-CDR, and CHIRPS exhibited the best results (r=0.68, r=0.67, and r=0.65, respectively).

The median of the correlation coefficients was about 0.70 (Fig. 3.4). The analysis of this metric showed that CHIRPS had the best result, followed by Ag-ERA5, and TerraClimate. The poor performance of CFS-2 stands out compared to the rest of the precipitation datasets, since this dataset severely overestimated precipitation in almost all stations. Regarding mean monthly precipitation (FIG. 4), datasets did not differ except for CFS-2, which had a greater dispersion than the rest of the models. This performance of the models was also similar considering RMSE, with CHIRPS having the lowest value (25.5 mm), while CFS-2 had the highest value (48.9 mm). This response pattern was analogous to the Standard Deviation measures.

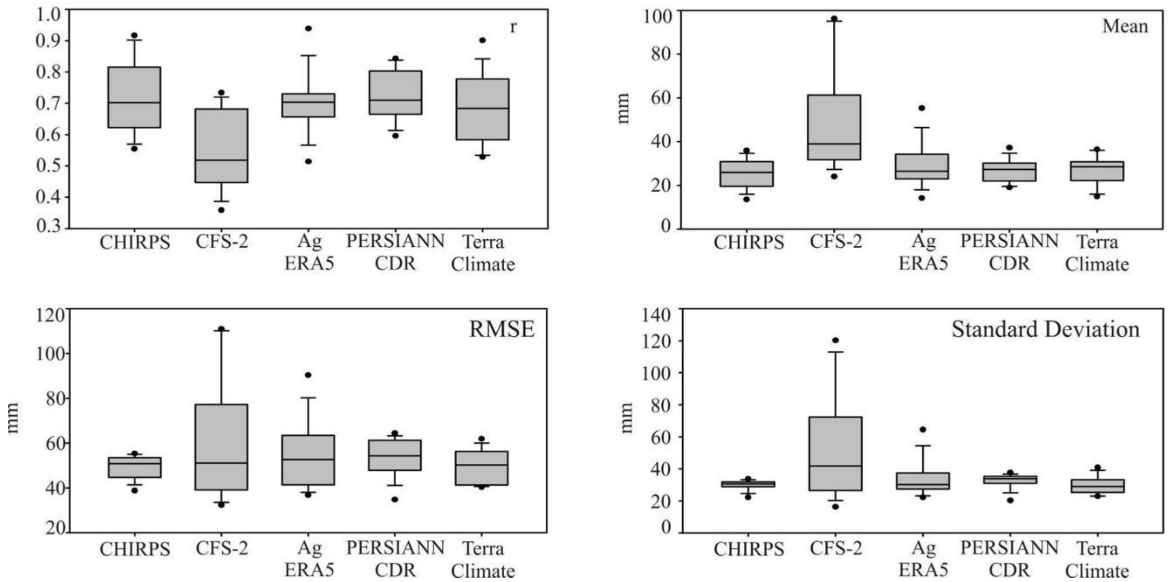


Fig. 3.4. Performance evaluation of five global precipitation datasets considering comparisons of correlation coefficients (r), means, Root Mean Square Errors (RMSE), and standard deviations for all rain gauge stations for monthly precipitation. Each boxplot was generated with the results of 14 stations.

Figure 3.5 shows the Taylor diagrams comparing the observed and the gridded monthly precipitation datasets at basin scale for Guadalupe (OPSE Guadalupe), Nazas-Santa Rosa (OPSE Mapimi), and San Rafael (OPSE El Tokio) for the years 1983 to 2018. The Taylor diagrams show the level of performance of the precipitation datasets in comparison to the observation data. For instance, CHIRPS and AgERA5 (r = 0.92) in Guadalupe basin; CHIRPS in the Nazas-Santa Rosa basin (r = 0.91), and AgERA5 in the San Rafael basin (r = 0.81). Regarding RMSE, in general, CFS-2 data showed the largest errors, while CHIRPS and AgERA5 data exhibited the smallest errors. The ability of CFS-2 to capture monthly precipitation at basin scale was overall relatively poor.

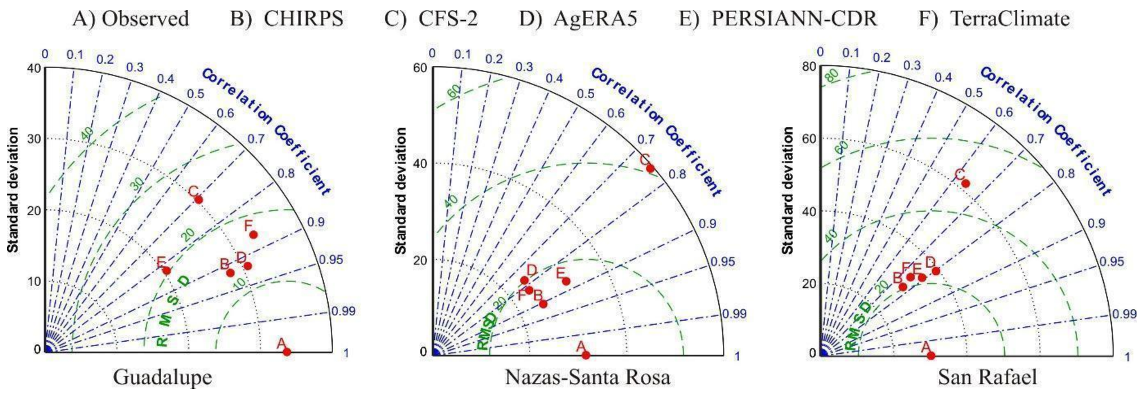


Fig. 3.5. Taylor diagrams comparing precipitation datasets (A to F) with rain gauge data in terms of correlation coefficients, standard deviations and Root Mean Square Errors for the Guadalupe (left), Nazas-Santa Rosa (center) and San Rafael (right) basins. The radial coordinate (y axis) provides the magnitude of standard deviation, and the concentric semi-circles are the RMSE values. The angular coordinate shows the correlation coefficient.

In this study, in Guadalupe basin the lowest difference in RMSE is reported with CFS-2 (24.04 and 24.62 mm for the nearest point and the basin average respectively) while the largest difference is observed with Terra Climate (14.89 and 17.08 mm for the nearest point and the basin average respectively). The Guadalupe basin has 9 stations that do not comply with quality control (Fig 3.2) therefore; the results in this basin should be taken with caution.

Considering the empirical cumulative distribution functions (ECDFs) for the observed precipitation and the global precipitation datasets (Fig. 3.6) for the Guadalupe basin, regarding the 95th percentil, TerraClimate present the 98 % of the observation value, while PERSIANN-CDR present the 57% of the observational value, indicating that the higher precipitation was underestimated by PERSSIAN-CDR dataset. For the Nazas-Santa Rosa and San Rafael basins, a relatively poor match between the observed and CFS-2 ECDFs data, shows that this database does not realistically reproduce the precipitation events over the catchments, as the probability curve is shifted towards more intense precipitation (Fig. 3.6b and 3.6c).

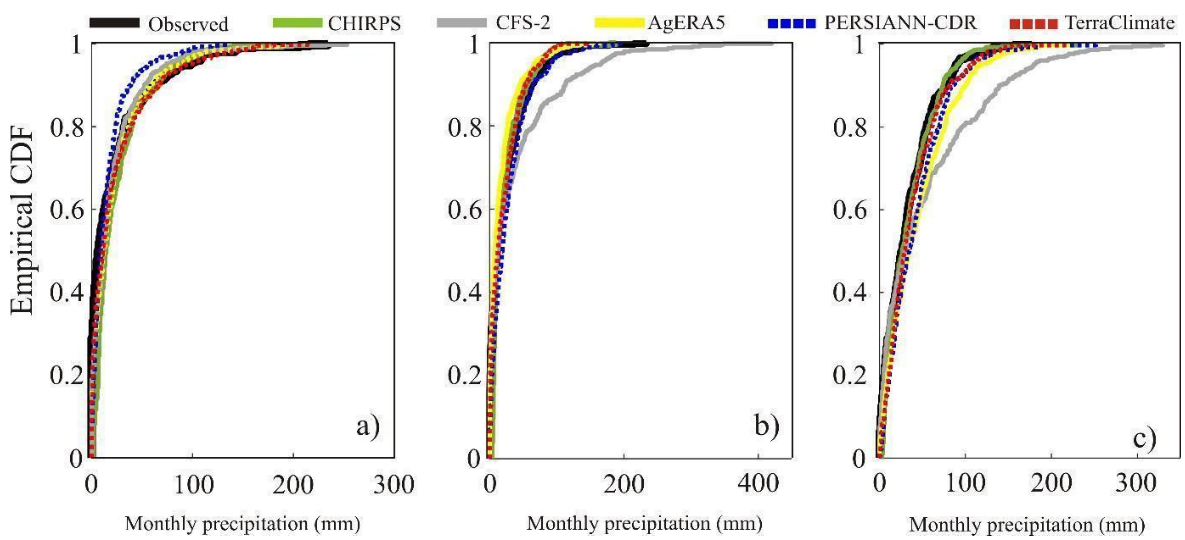


Fig. 3.6. Empirical cumulative distribution functions (ECDFs) for the observed and global datasets of precipitation at a monthly scale for a) Guadalupe, b) Nazas-Santa Rosa, and c) San Rafael basin for the years 1983 to 2018.

3.4.1 Annual precipitation variation

Considering the average annual rainfall for global precipitation datasets and gauge stations observations for 1983-2018 period (Fig. 3.7a), the station 2001 (OPSE Gpe) had 253 mm year^{-1} (1983-2018 period) compared to closest estimate of 255 mm year^{-1} with TerraClimate. CFS-2 exhibited the highest overestimation of annual rainfall in stations 10045 (OPSE Mapimí) (with average rainfall of 348 mm year^{-1} compared to estimates of 967 mm year^{-1}) and stations 19020 and 19182 (OPSE El Tokio); with average annual rainfall of 356 mm year^{-1} compared to estimates of 1091 mm year^{-1}; finally station 19182 presented 367 mm year^{-1} while estimates reached 1071 mm year^{-1}. On average for all gauge stations, TerraClimate overestimated annual rainfall by 4 %, followed by CHIRPS by 5 %, and CFS-2 by 37 %.

The five precipitation products adequately captured inter-annual rainfall variability in the Guadalupe basin (Fig. 3.7b). Annual gauge rainfall differed between 59 and 554 mm year^{-1}, while PERSSIAN-CDR varied between 62 and 515 mm year^{-1}, CHIRPS between 141 and 522 mm year^{-1}, CFS-2 between 83 and 579 mm year^{-1}, ERA5Ag between 120 and 590 mm year^{-1}, while TerraClimate between 101 and 669 mm year^{-1} and consequently had the widest spread among the five datasets. Overall, all precipitation datasets captured dry periods especially for the years 1989, 1999, and 2009, which have been the driest years in the Guadalupe basin during the study period (Del Toro and Gunter, 2016).

In the Nazas-Santa Rosa basin (Fig. 3.7c), the analysis showed that all products captured adequately the spatial distribution of rainfall, even though with considerable overestimations or underestimations. Annual rainfall generally range between 140 and 515 mm year^{-1}; with CFS-2 annual rainfall varied between 196 and 993 mm year^{-1} (around 62 % overestimation), followed by PERSSIAN-CDR with 146 and 507 mm year^{-1} (about18 % overestimation). CHIRPS rainfall varied between 139 and 401 mm year^{-1} (around 7 % underestimation), while Terra Climate varied between 108 and

408 mm year^{-1} (10 % underestimation). CFS-2 had the widest spread of the five datasets with respect to observed data (Fig. 3.7c).

For the San Rafael basin (Fig. 3.7d), all precipitation datasets presented an overestimation of precipitation compared to the observed values. Annual rainfall generally ranged between 134 and 709 mm year^{-1} with historical average precipitation of 396 mm year^{-1}. Considering the three basins, San Rafael had the highest observed precipitation, Guadalupe 254 mm year^{-1}, and Nazas-Santa Rosa 281 mm year^{-1}. CFS-2 rainfall varied between 223 and 1087 mm year^{-1} (around 62 % overestimation) followed by ERA5 Ag with 200 and 768 mm year^{-1} (about 35 % overestimation) (Fig. 3.7d). CHIRPS rainfall varied between 252 and 583 mm year^{-1} (with a minor overestimation of 4 %). The results suggest that CFS-2 and ERA5 Ag did not represent the annual rainfall pattern for San Rafael and consequently had the highest spread among the five datasets with respect to observed data.

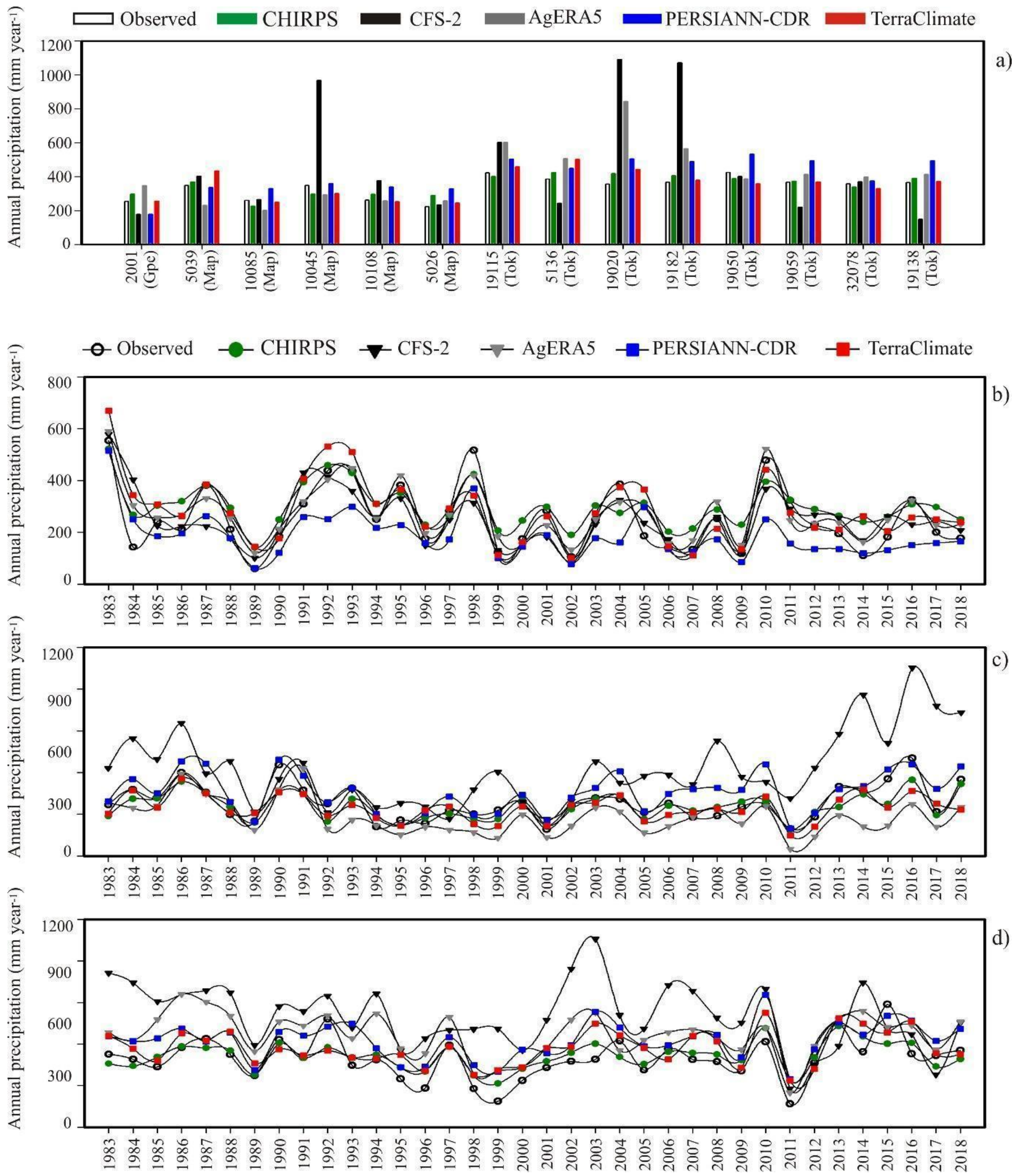


Fig. 3.7. Observed and estimated precipitation using five global datasets AgERA5, CHIRPS, CFS-2, PERSIANN-CDR, and TerraClimate depicting (a) average annual precipitation (n = 36 years) for selected stations (stations from left to right are in descending order of latitude from north to south) with the corresponding Social-Ecological Participatory Observatories (OPSEs) (Gpe = OPSE Guadalupe, Map= OPSE Mapimi, Tok = OPSE El Tokio). (b) Historical cumulative precipitation for the Guadalupe basin. (c) Historical cumulative precipitation for the Nazas-Santa Rosa basin. (d) Historical cumulative precipitation for the San Rafael basin.

Regarding the trend of annual precipitation (mm per year) (Table 3.3) for the Guadalupe basin, it was consistently negative for all selected precipitation datasets. Considering the Sen's slope value of the observed data in the Nazas-Santa Rosa basin, a positive trend was detected; considering CHIRPS, PERSIANN-CDR and CFS-2 the highest Sen's slope values were observed; while Ag-ERA5 and TerraClimate presented a negative trend. Regarding the San Rafael basin, the observed data followed a positive trend, as did CHIRPS, PERSIANN-CDR and TerraClimate; while a negative trend was found for CFS-2 and AgERA5. Although an overall negative trend was evident for the Guadalupe basin, considerable differences in trends of precipitation between the datasets occurred for the Nazas-Santa Rosa basin; and the San Rafael basins, where overall more positive trends were observed.

Table 3.3. Estimation of the trend of precipitation using Sen's slope considering observed gauge data and data of five global precipitation datasets for the Guadalupe, Nazas-Santa Rosa and San Rafael basins.

Basin	Observed	CHIRPS	CFS	AgERA5	PERSSIAN -CDR	Terra Climate
Guadalupe	-2.70	-1.70	-2.17	-1.60	-2.71	-3.91
Nazas -Santa Rosa	0.30	0.30	6.60	-2.20	1.90	-0.40
San Rafael	0.80	1.20	-6.70	-1.50	1.70	1.20

3.5 Discussion

At the global scale, the understanding and evaluation of the frequency and magnitude of extreme weather phenomena and climate change impacts require reliable meteorological data, especially in the dryland's regions with sparse rain-gauge data (Song et al., 2022). The current study used 36 years (1983 - 2018) of observed precipitation records from 14 rain gauges to evaluate the performance and accuracy of different global precipitation datasets for three dryland regions with distinct climatic patterns in northern Mexico. The relevance of choosing these regions is grounded in the need to provide reliable long-term datasets for the network of participatory social-ecological observatories (OPSE). The OPSEs all require reliable climate information as a basis to co-develop immediate and local action plans among stakeholders and thereby foster social innovations in response to high climate variability. These observatories compile and generate useful information for decision-making. While many local communities have their own (informal) indicator system for drought (considering social-ecological impact and response) based on experience and local knowledge of the territory, continuous weather monitoring is essential to increase the collection of accurate and high quality and reliable climatic data.

The altitudinal spatial distribution of the rain gauge stations for Guadalupe, with a winter rainfall regime, ranged between 0 and 500 m a.s.l.; for Mapimí, with summer rainfall regime, between 1100 and 1400 m a.s.l; and for El Tokio, with summer precipitation regime, between 1800 and 2100 m a.s.l. At the level of rain gauge stations in the study area, the results inferred that all global datasets performed distinctly in capturing the spatiotemporal characteristics at monthly and annual scales. AgERA5 exhibited the highest performance in the annual precipitation cycle in OPSE Guadalupe, CHIRPS provided the best estimation for the OPSE Mapimí, and AgERA5 for the OPSE El Tokio. The Guadalupe basin has only one gauge station to represent the basin. The RMSE was evaluated with the precipitation data obtained with the nearest single grid point to the gauge station and with the average of grid points within the basin. The implicit assumption of this methodology is that the pixels of the product are representative of the rain gauge stations observations (Baez et al. 2018b). Nevertheless, this assumption is not completely correct; for example, Dos Reis et al. (2017) validated satellite rainfall products over a mountainous watershed in a humid subtropical climate region of Brazil and found large errors when observations are compared with only one pixel data. Misrha (2013) analyzed the effect of rain gauge density over the accuracy of estimation of rainfall and found that MSE increases when the number of rain stations decreases. They concluded that 4–6 rain gauge stations from eight give reasonable accuracy in daily rainfall estimation in a 50 km × 50 km area. However, reduction to three or less rain gauges resulted in significant error. In this study, the overestimation/underestimation may be attributed to the fact that i) rainfall in the region is highly variable, ii) rain gauge density is low (Rincón et al., 2022), iii) and topography is rather irregular (orographic effects) (Mayor et al., 2017).

At the basin scale, the Taylor diagram showed that CHIRPS and AgERA5 had the same performance with respect to observed data for the Guadalupe watershed, while CHIRPS was more accurate in precipitation estimation for Nazas-Santa Rosa and for the San Rafael watershed, the best performance was reported with AgERA5. The results of this study are similar to those obtained by Rincón et al. (2022), who evaluated six precipitation datasets over Mexico, and the results showed that CHIRPS was the dataset with the highest performance. However, the authors concluded that the precipitation products presented a better performance in humid tropical and sub humid tropical areas than in arid areas. This conclusion is supported by Morales et al. (2021), who suggested that CHIRPS and ERA5 are the highest quality precipitation products over southern Mexico. In arid regions, overall contrasting results have been reported; for example, Rachidi et al. (2023) concluded that for estimating precipitation in the semi-arid region of Essaouira city in Morocco TerraClimate is the most appropriate product followed by PERSIANN-CDR, while CHIRPS showed a poor performance.

De Andrade et al. (2022) conducted an evaluation of five gridded precipitation products (including CHIRPS and TerraClimate) in tropical, semiarid and humid subtropical climatic zones in Northeast Brazil. They found that CHIRPS and the other two datasets were comparatively superior to the other products. The analysis considered the whole study area, so the specific performance of the products in the arid zone was not specified. The study of Helmi and Abdelhamed (2023) evaluated six satellite precipitation datasets including PERSIANN-CDR and CHIRPS over the arid area of the Kingdom of Saudi Arabia; yet the results showed poor accuracy in capturing the precipitation characteristics when comparing rain gauge measurements at different temporal resolutions. In a study in a semi dry basin of

Iran, PERSIANN-CDR revealed a discrepancy with the observed data and low accuracy in estimating precipitation (Eini et al., 2018); whereas in arid central Asia PERSIANN-CDR overestimated the precipitation, especially in winter (Song et al., 2022). Eini et al. (2022) suggest that PERSIANN-CDR has a better performance in estimating precipitation in humid areas than in arid areas; results supported by Zhu et al. (2016) which evaluated the precipitation estimated over humid regions in China.

Research groups in meteorology have developed several precipitation datasets (Funk et al., 2015a; Saha et al., 2014; Boogaard et al., 2020; Ashouri et al., 2015; Abatzoglou et al., 2018); while each of them presents a certain level of uncertainty, they are highly useful for characterizing wet and dry periods, especially in Mexican drylands where the spatial distribution of rain gauges is overall low. The simulation of precipitation depends on observational data to initialize forecast models; therefore, the accuracy of a model to generate estimates does not only depend on the model physics but on the availability of observational data (Nkiaka et al., 2017). Also, the heterogeneous topography is a critical factor that affects local precipitation patterns, as well as the spatial heterogeneity of the rain gauges, a situation that occurs in Mexico and other parts of the globe (Rincón et al., 2022).

Since the aim of this study was to use high resolution databases for small basins associated with the OPSEs, we selected databases that are constantly updated and thus suitable to work with them in a monitoring context. In fact, CHIRPS and AgERA5 are two databases that have a highest spatial resolution, 4.8 km and 9.6 km, respectively. The study basins are relatively small; for example, the Guadalupe

Basin measures about 93 x 23 km, so we selected datasets with a high-resolution grid in order to cover the basins' area. Other datasets present a coarse horizontal resolution that will not allow suite for local monitoring systems. In this study, CFS-2 had the lowest performance in precipitation estimation and is the database with the highest spatial resolution (~38 km).

This study provides a new contribution to the global perspective of the performance of the selected precipitation datasets; it is highly useful as a reference for several sectors including researchers, decision-makers, and local communities. The knowledge on historical climate variability based on accurate meteorological records taken in the field will allow generating a database of highly relevant information at the local and regional level, where local communities may be participatory stakeholders for future climate monitoring programs or campaigns. Brondízio et al. (2016) provides that local communities maintain intimate connections with their local ecosystems as a source of their livelihoods by adaptively managing their land, by local observations, and intergenerational transmission of knowledge. All these factors should be considered as key assets for establishing continuous long-term climate monitoring initiatives both to co-generate a highly reliable local database of precipitation and as a measure for adaptation to future climate conditions (Brondízio et al., 2016). In this context, the OPSEs promote community-based monitoring, where local communities contribute with data, information, knowledge, experiences on climate and nature, making these sources of information of high local and regional relevance for all sectors (academy, government, local communities, among others). This information needs to be standardized and incorporated into local and regional databases, so they can be directly accessed and used for farming activities of local communities. For example, a rancher would greatly benefit from local rainfall information collected in his/her pastures, as it reveals potentially relevant information on the temporal and spatial distribution of rainfall, which serves as input to livestock grazing management practices based on the presence of vegetation and forage linked to the presence of rain.

3.6 Conclusions

This study evaluated the accuracy of precipitation estimates of five global precipitation datasets (CHIRPS, CFS-2, AgERA5, PERSIANN-CDR, and TerraClimate) for three representative dryland regions in northern Mexico, by using observed precipitation for the years from 1983 to 2018 as a reference. At the rain gauge station level, results inferred that all precipitation datasets had a distinct efficiency in capturing monthly and annual precipitation cycles. This applied even for different stations within the same OPSE; we suggest this is due to high inherent variability of the rain in drylands, topography and/or rain gauge density. In case of a winter rainfall regime for the OPSE Guadalupe, CHIRPS consistently captured the annual cycle of precipitation followed by AgERA5. In case of a summer rainfall regime, CHIRPS and AgERA5 agreed when comparing observed rain-gauge data of annual precipitation cycles for the OPSEs Mapimí and El Tokio. At the basin level, CHIRPS and AgERA5 adequately reproduced the precipitation cycles at monthly and annual scales; besides the inter-annual variability was well captured. CFS-2 has the poorest performance with important underestimation or overestimation of precipitation at both the rain gauge station and basin scale. The overall ranking of highest to lowest suitability of the global precipitation products in this study corresponds to CHIRPS > AgERA5 > TerraClimate > PERSIANN-CDR > CFS-2.

In summary, the results allow us to distinguish between these products regarding the applications required for regions with little or no rainfall coverage. For Mexican drylands, based on the performance of the selected global precipitation datasets, we suggest using CHIRPS and AgERA5 to fill gaps of observational rain gauge information, for instance for hydrological modeling studies, drought monitoring, or management of water resources.

3.7 References

Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A. and Hegewisch. K. C., 2018: TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015, Scientific data, 5:170191, https://doi.org/10.1038/sdata.2017.191.

Alexandersson, H. and Moeberg, A., 1997: Homogeneization of Swedish temperature data. Part I: Homogeneity test for linear trends, International Journal of Climatology, 17, 25-34.

ASCE (American Society of Civil Engineers), 1996: Hydrology handbook. 2ª. New York, EE.UU. 769 p.

Ashouri, H., Hsu, K. L., Sorooshian, S., Braithwaite, D. K., Knapp, K. R., Cecil, L. D., Nelson, B. R. and Prat, O. P., 2015: PERSIANN-CDR: Daily Precipitation Climate Data Record from Multisatellite Observations for Hydrological and Climate Studies, Bull. Amer. Meteor. Soc., 96, 197–210, https://doi.org/10.1175/BAMS-D-13-00068.1.

Baez, G. A. D., Torres, M. M. J., Royo, M. M. H. and Kiniryd, J. R., 2018: Climate variability and trends in climate extremes in the priority conservation area El Tokio and adjacent areas in northeastern Mexico, Weather and Climate Extremes, 22, 36–47, https://doi.org/10.1016/j.wace.2018.10.001.

Baez, V. O. M., Zambrano-Bigiarini, M., Ribbe, L., Nauditt, A., Giraldo-Osorio, J. D., Thinh, N. X., 2018b: Temporal and spatial evaluation of satellite rainfall estimates over different regions in Latin-America, Atmospheric Research, 213, 34-50, https://doi.org/10.1016/j.atmosres.2018.05.011.

Boogaard, H., Schubert, J., De Wit, A., Lazebnik, J., Hutjes, R. and Van der Grijn, G., 2020: Agrometeorological indicators from 1979 to present derived from reanalysis. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), accessed 08 June 2023 https://doi.org/10.24381/cds.6c68c9bb.

Brondízio, E. S., Aumeeruddy-Thomas, Y., Bates, P., Carino, J., Fernández-Llamazares, Á., Ferrari, M. F., Galvin, K., Reyes, G. V., McElwee, P., Molnár, Z., Samakov, A. and Shrestha, U. B., 2021: Locally Based, Regionally Manifested, and Globally Relevant: Indigenous and Local Knowledge, Values, and Practices for Nature, Annual Review of Environment and Resources, 46, 481–509, https://doi.org/10.1146/annurev-environ-012220-012127.

Buishand, T. A., 1982: Some methods for testing the homogeneity of rainfall records. Journal of Hydrology, 58, 11-27.

Cerano, P. J., Esquivel, A. G., Sánchez, C. I. and Estrada, A. J. R., 2020: Analysis of meteorological droughts in the Yaqui River Basin, Mexico and its relationship with ENSO. Boletín de la Asociación de Geógrafos Españoles, 86, https://doi.org/10.21138/bage.2937.

CONABIO (Comisión Nacional para el Conocimiento y Uso de la Biodiversidad), 2023: Región Terrestre Prioritaria el Tokio (RTP 80). Available in: http://www.conabio.gob.mx/conocimiento/regionalizacion/doctos/rtp_080.pdf.

CONANP (Comisión Nacional de Áreas Naturales Protegidas), 2006: Programa de Conservación y Manejo de Reserva de la Biosfera de Mapimí, México. México D. F. Available in: https://simec.conanp.gob.mx/pdf_libro_pm/139_libro_pm.pdf.

De Andrade, J. M., Ribeiro, N. A., Alencar, B. U., Cavalcanti, M. A. C., Gico, L. S. M., Montenegro, L., 2022: A comprehensive assessment of precipitation products: Temporal and spatial analyses over terrestrial biomes in Northeastern Brazil. Remote Sensing Applications: Society and Environment, 28, 100842, https://doi.org/10.1016/j.rsase.2022.100842.

Del Toro, G. F. J., Gunter, K. T., 2016: Identificación de periodos de sequía histórica en una región de clima tipo semiárido mediterráneo. Revista Mexicana de Ciencias Agrícolas 7 (6), 1311-1320. Available in: http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S2007-09342016000601311.

Dorward P, Clarkson, G. and Stern, R, 2015: Participatory Integrated Climate Services for Agriculture (PICSA): Field Manual. Walker Institute, University of Reading. ISBN: 9780704915633, https://hdl.handle.net/10568/68687.

Dos Reis, J. B. C., Daleles, R. C., Sampaio, L. E. S., 2017: Validation of Satellite Rainfall Products over a Mountainous Watershed in a Humid Subtropical

Climate Region of Brazil. Remote Sensing 9, no. 12: 1240. https://doi.org/10.3390/rs9121240.

Eini, M.R., Javadi, S., Delavar, M. and Darand, M., 2018: Accuracy of PERSIANN-CDR precipitation satellite database in simulation assessment of runoff in SWAT Model on Maharlu Basin. Phys. Geogr. Res. Q., 50, 563–576, https://doi.org/10.22059/jphgr.2018.238898.1007096.

Eini. M., Rahmati, A. and Piniewski, M., 2022: Hydrological application and accuracy evaluation of PERSIANN satellite-based precipitation estimates over a humid continental climate catchment, Journal of Hydrology: Regional Studies, 41, https://doi.org/10.1016/j.ejrh.2022.101109.

Fernandez, P. C. A., Hatterman, F. F., Krisanova, V., Lovanova, A., Vega J. F., Lavado, W., Santini, W., Aybar, C. and Bronstert, A., 2022: A Novel High-Resolution Gridded Precipitation Dataset for Peruvian and Ecuadorian Watersheds: Development and Hydrological Evaluation. J. Hydrometeor., 23: 309-336, https://doi.org/10.1175/JHM-D-20-0285.1.

Funk, C., and Coauthors., 2015a: The climate hazards infrared precipitation with stations - A new environmental record for monitoring extremes. Scientific Data, 2, https://doi.org/10.1038/sdata.2015.66.

Funk, C., A. Verdin, J. Michaelsen, P. Peterson, D. Pedreros, and G. Husak, 2015b: A global satellite-assisted precipitation climatology. Earth Syst. Sci. Data, 7, 275–287, https://doi.org/10.5194/essd-7-275-2015.

Gelaro, R. and coauthors., 2017: The Modern-Era retrospective analysis for research and applications, version 2 (MERRA-2). Journal of Climate, 30, 5419–5454, https://doi.org/10.1175/JCLI-D-16-0758.1.

Halffter, G., 1984: Las Reservas de La Biosfera: Conservación de la naturaleza para el hombre. Acta Zoológica Mexicana, 5, 1–50, https://doi.org/10.21829/azm.1984.151926.

Harris, I., Osborn, T. J., Jones, P. and Lister, D., 2020: Version 4 of the CRU TS Monthly High-Resolution Gridded Multivariate Climate Dataset. Scientific Data, 7, 109, https://doi.org/10.1038/s41597-020-0453-3.

Helmi, A. M. and Abdelhamed, M. S., 2023: Evaluation of CMORPH, PERSIANN-CDR, CHIRPS V2.0, TMPA 3B42 V7, and GPM IMERG V6 Satellite Precipitation Datasets in Arabian Arid Regions, Water, 15, 92, https://doi.org/10.3390/w15010092.

Hersbach, H. and coauthors, 2020: The ERA5 global reanalysis. Q J R Meteorol Soc 146, 1999–2049, https://doi.org/10.1002/qj.3803.

Hinge, G., Mohamed, M. M., Long, D., Hamouda, M. A., 2021: Meta-analysis in using satellite precipitation products for drought monitoring: lessons learnt and way forward. Remote Sensing, 13 (21), 4353. https://doi.org/10.3390/rs13214353.

Huber-Sannwald, E., Martínez, T. N., Espejel, I., Lucatello, S., Coppock, D. L. and Reyes, G. V. M. 2020. Introduction: International Network for the Sustainability of Drylands—Transdisciplinary and Participatory Research for Dryland Stewardship and Sustainable Development. In: Lucatello, S., Huber-Sannwald, E., Espejel, I., Martínez, T. N., Eds. Stewardship of Future Drylands and Climate Change in the Global South: Challenges and Opportunities for the Agenda 2030. Springer Climate; Springer International Publishing: Cham, pp 1–24, https://doi.org/10.1007/978-3-030-22464-6_1.

Huffman, G. J. and Coauthors., 2007: The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. J. Hydrometeor., 8, 38–55, https://doi.org/10.1175/JHM560.1

Huffman, G. J. and Coauthors., 2020: NASA Global Precipitation Measurement (GPM) Integrated Multi-satellitE Retrievals for GPM (IMERG). In: V. Levizzani et al. (eds.), Satellite Precipitation Measurement, Advances in Global Change Research, 67, https://doi.org/10.1007/978-3-030-24568-9_19.

Huntington, J. L., Hegewisch, K. C., Daudert, B., Morton, C. G., Abatzoglou, J. T., McEvoy, D. J. and Erickson, T., 2017: Climate Engine. Cloud Computing and Visualization of Climate and Remote Sensing Data for Advanced Natural Resource Monitoring and Process Understanding. American Meteorological Society, https://doi.org/10.1175/BAMS-D-15-00324.1.

INEGI (Instituto Nacional de Estadística y Geografía), 2023: Simulador de Flujos de agua de cuencas hidrográficas. Accessed 12 April 2023 Available in: https://antares.inegi.org.mx/analisis/red_hidro/siatl/

Jiang, S., Ren, L., Hong, Y., Yong, B., Yang, X., Yuan, F. and Ma, M., 2012: Comprehensive Evaluation of Multi-Satellite Precipitation Products with a Dense Rain Gauge Network and Optimally Merging Their Simulated Hydrological Flows Using the Bayesian Model Averaging Method. Journal of Hydrology, 452–453, 213–225, https://doi.org/10.1016/j.jhydrol.2012.05.055.

Joyce, R. J., Janowiak, J. E., Arkin, P. A. and Xie, P., 2004: CMORPH: A Method that Produces Global Precipitation Estimates from Passive Microwave and Infrared Data at High Spatial and Temporal Resolution. J. Hydrometeor., 5, 487-503. https://doi.org/10.1175/1525-7541(2004)005%3C0487:CAMTPG%3E2.0.CO;2.

Kobayashi, S. and coauthors., 2015: The JRA-55 reanalysis: General specifications and basic characteristics. Journal of the Meteorological Society of Japan, 93, 5–48, https://doi.org/10.2151/jmsj.2015-001.

Liu, Z., Wang, T. and Yang, H., 2023: Overestimated Global Dryland Expansion with Substantial Increases in Vegetation Productivity under Climate Warming. Environ. Res. Lett., 18, (5), https://doi.org/10.1088/1748-9326/accfb1.

Martinez, L. C., Huber-Sannwald, E., Valdéz, H. S. D., Aguilera, J. C. L., Lucatello, S., Tagüeña, M. N., Páez, M. R. I., Gómez, R. V. M., and Seingier, G., 2021: Métodos colectivos para tejer el camino desde la desertificación al desarrollo sostenible: los Observatorios Participativos Socio-Ecológicos. Ecosistemas, 30, 2232–2232, https://doi.org/10.7818/ECOS.2232.

Mayor, Y., Tereshchenko, I., Fonseca-Hernández, M., Pantoja, D. and Montes, J., 2017: Evaluation of error in IMERG precipitation estimates under different topographic conditions and temporal scales over Mexico. Remote Sensing, 9, (5), 503, https://doi.org/10.3390/rs9050503.

Miranda, J. L. G., 2002: Precipitation Estimation Over Mexico Applying PERSIANN System and Gauge Data. The University of Arizona. Available from: http://hdl.handle.net/10150/206869.

Mishra, A. K., 2013: Effect of rain gauge density over the accuracy of rainfall: a case study over Bangalore, India. SpringerPlus 2, 311, https://doi.org/10.1186/2193-1801-2-311.

Molina, N. E., Hallack, A. M., Martínez, P. S., Ramírez, H. J., Mungaray, M. A. and Sastre, M. A., 2016: Hydrological modeling and climate change impacts in an agricultural semiarid region. Case study: Guadalupe River basin, Mexico. Agricultural Water Management, 175, 29-42, http://dx.doi.org/10.1016/j.agwat.2015.10.029.

Morales, V. M. I., Herrera, G. d. S., Aparicio, J., Rafieeinasab, A. and Lobato, S. R., 2021: Evaluating reanalysis and satellite-based precipitation at regional scale: a case study in southern Mexico, Atmósfera, 34, (2), https://doi.org/10.20937/ATM.52789.

Nkiaka, E., Nawaz, N. R. and Lovett, J. C., 2017: Evaluating global reanalysis precipitation datasets with rain gauge measurements in the Sudano-Sahel region: case study of the Logone catchment, Lake Chad Basin. Meteorological Applications, 24: 9–18, https://doi.org/10.1002/met.1600.

Pettitt, A. N., 1979: A nonparametric approach to the change point detection. Applied Statistics, 28, 126-135.

Prakash, S., 2019: Performance assessment of CHIRPS, MSWEP, SM2RAIN-CCI, and TMPA precipitation products across India. Journal of Hydrology, 571, 50–59, https://doi.org/10.1016/j.jhydrol.2019.01.036.

Prăvălie, R., Bandoc, G., Patriche, C. and Sternberg, T., 2019: Recent Changes in Global Drylands: Evidences from Two Major Aridity Databases. Catena, 178, 209–231, https://doi.org/10.1016/j.catena.2019.03.016.

Rachidi, S., El Mazoudi, E. H., El Alami, J., Jadoud, M. and Er-Raki, S., 2023: Assessment and Comparison of Satellite-Based Rainfall Products: Validation by Hydrological Modeling Using ANN in a Semi-Arid Zone. Water, 15, https://doi.org/10.3390/w15111997.

Reichle, R. H., Q. Liu, R. D. Koster, C. S. Draper, S. P. P. Mahanama, and G. S. Partyka., 2017: Land surface precipitation in MERRA-2. Journal of Climate, 30, 1643–1664, https://doi.org/10.1175/JCLI-D-16-0570.1.

Reyes, G. V. M., Huber-Sannwald, E., Tagüeña, M. N., Espejel, C. I., Lucatello, S., Bowker, M. and Martínez, L. C., 2021: Long-Term Socio-Ecological Research in the Biosphere Reserve in Mapimí, Mexico: A Multidimensional Participatory Observatory of Rangeland/Pastoral Systems. International Grassland Congress Proceedings. Available in: https://uknowledge.uky.edu/cgi/viewcontent.cgi?article=4343&context=igc.

Rincón, A. P., Khouakhic, A., Mendoza, C. O., López de la C. J. and Paredes, B. K. M., 2022: Evaluation of satellite precipitation products over Mexico using Google Earth Engine Journal of Hydroinformatics, 24 (4), 711-729, https://doi.org/10.2166/hydro.2022.122.

Saha, S. and Coauthors., 2010: The NCEP Climate Forecast System Reanalysis. Bulletin of the American Meteorological Society, 91 (8), 1015–1058, https://doi.org/10.1175/2010BAMS3001.1.

Saha, S. and Coauthors., 2014: The NCEP climate forecast system version 2. Journal of Climate, 27, 2185–2208, https://doi.org/10.1175/JCLI-D-12-00823.1.

Santes, A. R. V. and Camacho, G. A., 2018: Escasez hídrica y vitivinicultura en Valle de Guadalupe, Baja California, México. La percepción de los productores. Revista española de estudios agrosociales y pesqueros, 249, 63–89. Available in: https://www.mapa.gob.es/ministerio/pags/Biblioteca/Revistas/pdf_REEAP%2FPdf_REEAP_r249_63_89.pdf

Schneider, U., Becker, A., Finger, P., Rustemeier, E. and Ziese, M., 2020: GPCC Full Data Monthly Version 2020 at 0.25°: Monthly Land-Surface Precipitation from Rain-Gauges Built on GTS-Based and Historic Data: Gridded Monthly Totals. Global Precipitation Climatology Centre (GPCC). Accessed 15 May 2023 https://doi.org/10.5676/DWD_GPCC/FD_M_V2020_025.

SEMARNAT (Secretaría de Medio Ambiente y Recursos Naturales), 2018: Informe del Medio Ambiente en México. Cap. 3. Suelos. 43 pp. https://apps1.semarnat.gob.mx:8443/dgeia/informe18/tema/pdf/Cap3_Suelos.pdf.

Sen, P. K., 1968: Estimates of the regression coefficient based on Kendall's tau. J. Am. Stat. Assoc. 63, 1379–1389, https://doi.org/10.1080/01621459.1968.10480934.

SMN (Servicio Meteorológico Nacional), 2024a: Datos mensuales de precipitacion estacion Agua caliente (2001). Availabe in:

https://smn.conagua.gob.mx/tools/RESOURCES/Normales_Climatologicas/Mensuales/bc/mes02001.TXT

SMN (Servicio Meteorológico Nacional), 2024b: Datos mensuales de precipitacion estacion Laboratorio del desierto (10165). Availabe in: https://smn.conagua.gob.mx/tools/RESOURCES/Normales_Climatologicas/Mensuales/dgo/mes10165.TXT.

SMN (Servicio Meteorológico Nacional), 2024c: Estaciones climatológicas 2020. Availabe in: https://smn.conagua.gob.mx/tools/RESOURCES/estacion/EstacionesClimatologicas.kmz.

Song, L., Xu, C., Long, Y., Lei, X., Suo, N. and Cao, L., 2022: Performance of Seven Gridded Precipitation Products over Arid Central Asia and Subregions. Remote Sensing, 14, 6039, https://doi.org/10.3390/rs14236039.

Spinoni, J. and coauthors., 2020: A. Future Global Meteorological Drought Hot Spots: A Study Based on CORDEX Data. Journal of Climate, 33 (9), 3635–3661, https://doi.org/10.1175/JCLI-D-19-0084.1.

Sun, Q., Miao, C., Duan, Q., Ashouri, H., Sorooshian, S. and Hsu, K. L., 2018: A Review of Global Precipitation Data Sets: Data Sources, Estimation, and Intercomparisons. Reviews of Geophysics, 56, 79–107, https://doi.org/10.1002/2017RG000574.

Tamm, O., Saaremae E., Rahkema, K., Jaagus, J. and Tamm, T., 2023: The intensification of short-duration rainfall extremes due to climate change – Need for a frequent update of intensity–duration–frequency curves. Climate Services, 30, https://doi.org/10.1016/j.cliser.2023.100349.

Tan, X., Wu, Y., Liu, B. and Chen, S., 2020: Inconsistent changes in global precipitation seasonality in seven precipitation datasets. Clim. Dynam., 54, 3091–3108, https://doi.org/10.1007/s00382-020-05158-w.

Taylor, K. E., 2001: Summarizing multiple aspects of model performance in a single diagram. Journal of Geophysical Research: Atmospheres, 106, 7183-7192, https://doi.org/10.1029/2000JD900719.

UNE (United Nations Environment), 1997: World Atlas of Desertification: Second Edition. Available in: https://wedocs.unep.org/xmlui/handle/20.500.11822/30300.

Velázquez, J. A. and Talledos, E., 2018: Comparación del uso de datos meteorológicos observados y procesados en malla en la simulación hidrológica de eventos extremos en una cuenca en México. In: Esteves, R. J. M., Welsh, R. C. M., Romo, A. M. L. and Travieso, B. A. C. (coord.), 2018: Riesgo de desastres en México: eventos hidrometeorológicos y climáticos, Instituto Mexicano de Tecnología del Agua, 440 p. Available in:

https://www.imta.gob.mx/biblioteca/libros_html/desastres-mexico/Libro-Riesgo-desastres-en-Mexico.pdf.
Velázquez J.A. and Talledos E., 2019: La medición de variables hidrometeorológicas en la Huasteca potosina: entre lo institucional y lo local. In: Peña F. (coordinador). Aguas turbulentas y prácticas locales y comunitarias en la Huasteca. Riesgos hídricos y organización social. El Colegio de San Luis, A.C.
Xu, R., Tian, F., Yang, L., Hu, H., Lu, H. and Hou, A., 2017: Ground Validation of GPM IMERG and TRMM 3B42V7 Rainfall Products over Southern Tibetan Plateau Based on a High-Density Rain Gauge Network. Journal of Geophysical Research: Atmospheres, 122, 910–924, https://doi.org/10.1002/2016JD025418.
Zhu, Q., Xuan, W. D., Liu, L. and Xu, Y. P., 2016: Evaluation and hydrological application of precipitation estimates derived from PERSIANN-CDR, TRMM 3B42V7, and NCEP-CFSR over humid regions in China. Hydrol. Process., 30, 3061–3083, https://doi.org/10.1002/hyp.10846.
Zomer, R.J., Xu, J. and Trabucco, A., 2022: Version 3 of the Global Aridity Index and Potential Evapotranspiration Database. Scientific Data, 9, 409, https://doi.org/10.1038/s41597-022-01493-1.

Chapter 4

---

4. Future meteorological droughts in social-ecological participatory observatories in Mexico drylands and understanding of an adaptative responses to drought by local communities

4.1 Abstract

Meteorological drought has been an inevitable natural phenomenon throughout Mexican history tightly linked to its geographic location and has had severe and long-lasting impacts on humans and ecosystems. These phenomena are usually quantified by so-called drought indices, which are indirect indicators based on climatic information. The Standardized Precipitation Index (SPI) is one of the most widely used indices and this study attempts to characterize the occurrence of this index in a network of dryland systems associated with local Social–Ecological Participatory Observatories (OPSEs by its Spanish acronym) along a west–east transect in northern Mexico over the 21st century. In particular, I addressed the following questions: To what extent will the projected meteorological drought become more frequent and sever during the 21st century for the OPSE network? How do the local communities perceive the drought concept and what main strategies of adaptation have been adopted when facing the risks of droughts in the OPSE Mapimí? The SPI was calculated at a 12-months time scale for three periods, being 1981–2010 representing the reference period; and 2040-2070 and 2071–2100 representing the near and far future. For the historic period we use the monthly

precipitation global datasets CHIRPS and for the future period montly precipitation simulation from the CanRCM4 (NA-CORDEX) considering the future scenario (Representative Concentration Pathway) RCP 8.5 (scenario that describes a future of high greenhouse gas emissions) was used to analyze meteorological droughts (frecueny, duration and intensity In adittion, perceptions of drought in the past by local communities and responses adaptative measures in the OPSE Mapimí were explored through of face-to-face interviews during October 2021 to February 2022 by semi-structured interview schedule. We discovered, that in the 2041-2070 period, the RCP 8.5 scenario project an increase in average annual precipitation for the OPSE Guadalupe and Mapimi of 8 %, Comcaac of 7 %, and an idrecrease for the OPSE Cuauhtémoc of 3 % and El Tokio of 8 %. For the period 2071-2100, the RCP 8.5 scenario project an increase in average annual precipitation for the OPSE Guadalupe of 28 %, Comcaac of 27 %, Cuauhtémoc of 16 %, Mapimi of 24 % and El Tokio of 3 %. Projections of future meteorological droughts generally denote a decrease in their frequency, duration and intensity for the OPSEs network (2040-2100). In the OPSE Mapimí, the different local communities related drought commonly as no rain followed by no forage. The years 1989, 1995, 1998, 2001, 2002, 2008, and 2010 were reported to have been characterized by the most relevant drought events, since they affected their living conditions. Droughts outside the period analyzed (1981-2010) were identified, e.g. in the 1950s and 1970s, and recently in the year 2019. The major past “changes in climate” perceived by the local communities were the following: in the past there was more rain (31%), currently there is no defined rainy season (23%), it's hotter now than in the past (29%), perceive more frequent droughts (3%) and the cold is more extreme now than before (14%). Finally, the most severe impacts of drought were related to livestock deaths, low salt production and migration of people to nearby cities or states or to United States.

4.2 Introduction

In the context of climate change, examining alterations in rainfall patterns is a crucial area of research because human activities are highly susceptible to extreme weather events such as excessive or insufficient rainfall (Magallanes et al., 2024). Drought is one of the most extreme meteorological events that occurs in most parts of the world and affects the availability of water related to both surface and subsurface water sources (Faiz et al., 2020; Gond et al., 2023). Its frequency, duration and magnitude are projected to increase in many regions around the globe (Ukkola et al., 2020), yet climate model projections remain uncertain (Ukkola et al., 2020; Wang et al., 2020). According to a recent assessment by the ECJRC-UNCCD (European Commission Joint Research Centre and United Nations Convention to Combat Desertification) (2024), the UNCCD Science –Policy Interface (SPI) (2024) and Vicente-Serrano et al., (2024), planet Earth has become more arid. Therefore, the queation arises, how does an increase in aridity influence drought patterns? Drought is a systemic phenomenon that cuts across sectors and systems, creating compound and cascading impacts that are difficult to estimate and predict (ECJRC-UNCCD, 2024). However, the understanding of the characteristics and occurrences of droughts are major issues aiming to prevent and mitigate the consequences of future occurrences (Lorenzo et al., 2024).

Droughts usually start with insufficient rainfall (meteorological drought) and propagate through the hydrological cycle over a period of time to affect soil moisture (agricultural drought) and then runoff, groundwater aquifers, and water reservoirs (hydrological drought) (Wilhite, 2000; Mishra and Singh, 2010;; Li et al., 2024). Over the years, there has been much discussion about which drought indices should be used based on climate applications, drought causes and effects, or the different levels of availability of information for each region. Different variables are commonly involved in drought assessments, such as precipitation, air temperature, or evaporation. Thus, different indices have been developed to investigate droughts in detail, some that use a single variable and others using several parameters (Lorenzo et al., 2024).

The Standardized Precipitation Index (SPI) developed to define and monitor droughts, considers rain as the only variable to determine whether there is a deficit or excess of precipitation in a particular region and period under normal conditions (McKee et al., 1993). It is one of the most widely-used indices in Mexico to monitor agricultural drought allowing to determine dry and wet events at a particular time scale for any location that has a precipitation record (Salas et al., 2021) or to precipitation zoning (Giddings et al., 2005; Magallanes et al., 2024). The main advantage of SPI is that it can be calculated for different time scales (typically ranging from one to 48 months) (Lorenzo et al., 2024). Thus, for example, the 3-

month SPI provides a comparison of the precipitation over a specific 3-month period with the precipitation totals from the same 3-month period for all the years included in the historical record. In other words, a 3-month SPI at the end of February compares the December–January– February precipitation total in that particular year with the December–February precipitation totals of all the years on record for that location. A 3-month SPI reflects short- and medium-term moisture conditions and provides a seasonal estimation of precipitation. While, a 12-month up to 24-month SPI are usually tied to streamflows, reservoir levels, and even groundwater levels at longer timescales (WMO, 2012; EDO, 2025).

The main criticism of the SPI is that its calculation is based solely on precipitation data and consequently accounts for drought events induced by a lack of rainfall (Lorenzo et al., 2024). Nevertheless, this drought index is still one of the most widely used worldwide, including Mexico. The United States Drought Monitor (USDM, 2000), the North American Drought Monitor (NADM, 2002), the Mexican Drought Monitor (MDM, 2014), the Western Regional Climate Center (WRCC, 2016), the National Integrated Drought Information System (NIDIS, 2024), among others, have integrated this index for detecting and characterizing meteorological droughts at level national and international. In fact, this index has been used in several recent studies to analyze meteorological droughts in the Mexican territory.

(Castillo et al. (2017) conducted a temporal and spatial analysis of drought in the Fuerte River Basin at Northwest of México for the period 1961 to 2012. They concluded that droughts have altered its occurrence patterns and presents with more frequency, intensity and duration in the last decades. It was found two periods with extremes droughts, from 1999 to 2004 and from 2011 onwards. The study of the distribution of drought showed that the areas most affected by this phenomenon are located in the upper and middle part of the basin. Escalante and Nuñez (2017) projected that under the RCP 8.5 scenario, the northern and northwestern parts of Mexico would suffer from a drought every 4.7 years in the far future (2075–2099) and that the regional mean annual precipitation would be only 408 mm during drought episodes. In another study, Velázquez (2023) evaluated three high-resolution datasets (NOAA, CHIRPS and PERSIANN-CDR) and compared them with observed precipitation (1983-2013) to capture wet and dry periods (1983-2013). According the SPI, results show good correlation, but extremely dry events are generally underestimated with CHIRPS and PERSIANN-CDR. The NOAA dataset performs better for wet events.

In recent decades, many studies have reported an overall global tendency toward more frequent and severe meteorological drought events (Spinoni et al., 2014; Osborn et al., 2016) even though the consensus about the extent and magnitude of the change is not universal (Seneviratne, 2012). Some studies have attempted to investigate global drought over the 21-st century (Touma et al. 2015; Spinoni et al., 2020). However, studies in Mexico at local scale on the forecasts of drought using the SPI to simulate how drought will develop in the future (2040-2100) are still scarce (Velázquez, 2023).

While drought risk is growing worldwide, the impacts are not felt evenly (Li et al., 2024). It affects millions of people each year and adversely impacts society, economy, and environment worldwide (Marengo et al., 2017; Spinoni et al., 2018; Vicente-Serrano et al., 2020). Among the top 10 worldwide disasters in the past50 years (1970–2019), drought was the deadliest, causing 650,000 deaths and far more economic losses thanother meteorological disasters (WMO, 2021). It is illustrated that drought has become a worldwide problem withattached adverse effects to the globe (Zhou et al., 2023). Even what constitutes drought may vary from one region, biome, and society to another, as the experience of a dry period may depend on the adaptive capacity and resources of local ecosystems and human communities. Therefore, the complexity of drought risk demands cross-sectoral policies accounting for regional diversity, leveraging local knowledge and promoting communities' engagement (ECJRC-UNCCD, 2024).

The International Network for Dryland Sustainability (RISZA by its Spanish acronym) addresses the grand social-ecological challenges emerging in Mexico's drylands with a transdisciplinary focus (Huber-Sannwald et al., 2020). One of RISZA's modus operandi are the Social-Ecological Participatory Observatories (OPSE) understood as living laboratories in dryland territories, where a key purpose of the OPSE is co-produce, share, exchange and store knowledge to jointly develop local action plans and to facilitate decision making in the context of the drylands social-ecological systems (Lauterio et al., 2021). In March 2021, a broad survey was conducted among diverse stakeholders associated with the network of five OPSEs in order to identify the priority issues and/or problems associated with each of the five OPSEs.

The results showed that drought, climate change, and water scarcity were the main key themes that affect the communities in the dryland regions of the OPSE.

Hence, the research presented in this study focused on meteorological drought, which has been recurring natural phenomenon throughout Mexican history (Dobler and Bocco, 2021). While the concept of meteorological drought is very well adopted by the scientific community, rather little is understood on how local communities of the arid and semiarid regions of Northern Mexico, especifically associated with the OPSEs, experience, perceive and respond to droughts. It is also questionable if local communities perceive meteorological drought, or whether the context in which this term is commonly used refers to something more complex. It is fundamentally important to learn about the integrated understanding of drought by local communities, because any attempts to understand and support the adaptive capacity of local communities should take into account this local environmental knowledge.

This study aims to answer the following questions: To what extent will the projected meteorological drought become more frequent and sever during the 21st century in the regions of the OPSE network? How do local communities perceive drought and which have been the main strategies to adapt to the risks of droughts in the OPSE Mapimí? Hence, the objective of this study was to evaluate drought characteristics and to compare monthly precipitation for the historical period (1981-2010) with future projections (2041–2100) of drought under the most extreme Representative Concentration Pathway (RCP) 8.5 scenario (van Vuuren et al. 2011). This RCP is characterized by increasing greenhouse gas emissions over time, representative of scenarios in the literature that lead to high greenhouse gas concentration levels (Riahi et al., 2011).

We apply the SPI at 12-month time interval to assess annual drought patterns, and therby evaluate future meteorological drought patterns considering the network of dryland systems associated with the OPSEs along a west–east transect reaching from the Mediterranean climate in northwest (NW) Mexico, coastal arid climate in the Sonora Desert, and semiarid climate in the Chihuahua Desert in central and east Mexico for the 21st century. In addition, this study seeks to explore the deep understanding, experience and perception of drought at the local level by the local communities and the main drought impacts that are perceived and identified by local actors. The knowledge of this information holds great importance considering both regional decision-makers and national policy-makers, as it may enable them to adjust suitable support programs that consider action pathways in accordance with the adaptative capacity to adapt local limitations specifically in relation to water scarcity.

4.3 Methods

4.3.1 Study área

Over 60 percent of Mexico is characterized by dry climates due to the domination of the subtropical high pressure system (approximately between 15°N and 30°N) and also due to two major topographic water-vapor barriers of N-S striking mountain ranges, the Sierra Madre Occidental and the Sierra Madre Oriental (Escalante and

Nuñez, 2017). The northern and northwestern parts of Mexico are even drier primarily due to the limited access of the Intertropical Convergent Zone (ITCZ); mean annual precipitation is less than 500 mm and nearly 68 % of the rainfall falls between June and September (CONAGUA, 2018). The Social–Ecological Participatory Observatories are situated along the west-east transect of dryland Mexican territory between latitudes 23° and 32° N and between longitudes 99 and 116 ° W (Fig. 4.1).

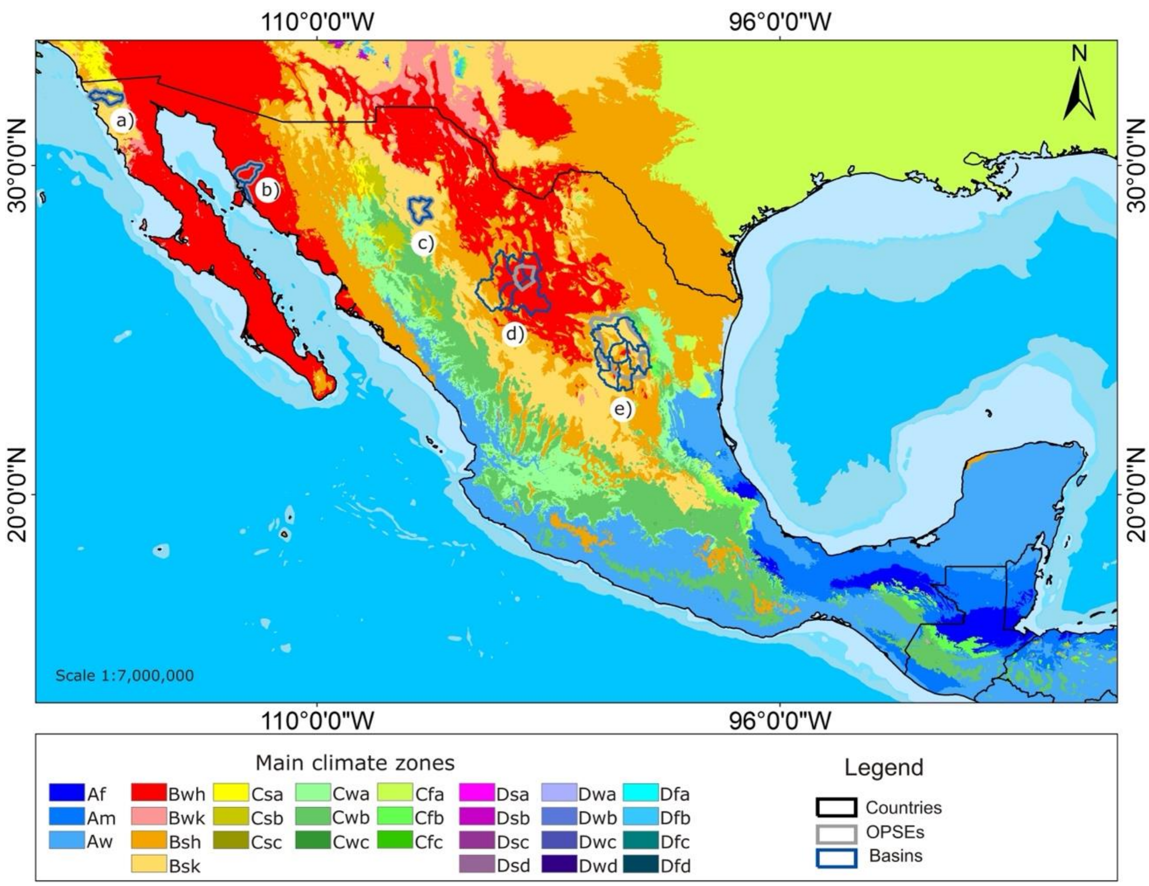


Fig. 4.1. Location of the Social–Ecological Participatory Observatories (OPSEs) along a west-east transect of Mexican drylands territory: a) OPSE Guadalupe; b) OPSE Comcaac; c) OPSE Cuauhtémoc; d) OPSE Mapimí, and e) OPSE El Tokio. The central shows the distribution of climate types across Mexico based on the Köppen-Geiger climate classification (Beck et al., 2018).

The OPSE Guadalupe is located in the northwest of Baja California, México. The region has an arid Mediterranean climate (climate classification BSk; Beck et al., 2018); the rainy season has a rainfall winter regime from December to March, with an annual average of 256.5 mm and an annual mean temperature of 18.2 °C (calculated with the historical average of the weather station Agua Caliente for the period 1970-2023) (SMN, 2025a). The region has an area of about 2,402 km^2 and the altitude varies between 0–1880 meters above sea level (masl) (INEGI, 2025).

The OPSE Comcaac refers to the area inhabited by the Indigenous community Comcaac of former hunter-gatherers living next to the Gulf of California, in the Sonoran Desert (Martínez and Renteria, 2020). The region has an arid, warm climate (climate classification BWh; Beck et al., 2018). There is no network of weather stations in this region, there is only the record of one meteorological station, however, time-series present incomplete data. Between 1981 and 2024 annual precipitation averaged 122 mm and annual mean temperature of 22 °C, calculated using global climate data series (satellite and reanalysis data) (CE, 2025). The region has an area of about 5,155 km^2 (The Infiernillo and San Ignacio basins have 3,947 km^2 and Isla Tiburon 1,208 km^2) (INEGI, 2025; Narchi et al., 2015). The altitude varies between 0 and 1140 m a.s.l. (INEGI, 2025). The OPSE Cuauhtemoc is located in the basin of the Laguna de Bustillos, in the Chihuahua State. The region has a semi arid climate (climate classification Bsk; Beck et al., 2018) and the rainy season has a rainfall summer regime, from May to October, with an average annual precipitation of 415 mm and annual mean temperature of 14 °C (Alatorre et al., 2014). The basin has an area of 3,264 km^2 and the altitude varies between 1980 and 2900 m a.s.l. (INEGI, 2025).

The OPSE Mapimí is located in the Chihuahuan desert in the southern area of the "Bolsón de Mapimí" between the Mexican states of Durango, Coahuila, and Chihuahua. This region is characterized by an arid climate (climate classification BWh; Beck et al., 2018) and the rainy season has a rainfall summer regime, from June to October, with an average annual of 248 mm and annual mean temperature of 20 °C (SMN, 2025b). Finally, El Tokio OPSE is located in northeastern Mexico, within the state boundaries of Coahuila, Zacatecas, Nuevo León and San Luis Potosí. This area is characterized by a dry semiarid climate (climate classification Bsk; Beck et al., 2018) with average annual precipitation of 492 mm, while the average annual temperature is 16.8 °C (Baez et al., 2018).

4.3.2 Precipitation data

The network of weather stations in Mexico is extensive. However, time-series often present incomplete data or less than 20 years of information. In this chapter, for the historic period we use the monthly precipitation global datasets CHIRPS, which is a satellite-based precipitation product developed by the U.S. Geological Survey and the Climate Hazard, with a spatial resolution of 0.05° x 0.05° (5.4 km); it covers 50° S– 50° N and 180° W–180°E; and its time series spans from 1981 at present (Funk et al. 2015). The CHIRPS datasets were obtained using the Climate Engine (CE,

2025) platform (https://app.climateengine.com/climateEngine) and the spatial domain of the OPSEs were the hydrological basins (Huntington et al. 2017). For Mexican drylands, CHIRPS has been documented as an appropriate data series for the estimation of precipitation at locations where no observed data are available (Esquivel et al., 2024).

For the future period 1940-2100, monthly precipitation simulation data were downloaded from the North American (NAM) domain from the Canadian Regional Climate Model 4 (CanRCM4) with a spatial resolution of 0.44°. The Canadian Centre for Climate Modelling and Analysis (CCCma) developed the CanRCM4, which is a component of the Canadian Earth System Model (CanESM) (Scinocca et al., 2016). This data series includes climatic simulations for the historical (1950 to 2005) and the future (2006-2100) period. In this chapter, Representative Concentration Pathways (RCPs) 8.5 scenario mentioned in the fifth assessment report (AR5) was used.

The climate change impact studies are often based on global climate model (GCM) simulations dynamically downscaled by a regional climate model (RCM) instead of direct GCM simulations (Velázquez et al., 2018). Numerous efforts and computational resources have beencommitted to developing RCMs, which produce simulations that try to better resolve the representation of com-plex surface characteristics (e.g., topography and land–sea contrast) (Torma et al., 2015) and small-scale atmo-spheric processes that are important drivers of regionalclimates (Di Luca et al. 2012). The typical use of regional climate models is to study climate processes in more detail than global models allow (Rummukainen, 2010). For this chapter, the monthly precipitation series were processed using Python 3 libraries Numpy, and netCDF4. The gridded monthly precipitation datasets were created by averaging the cell center values within the spatial domain of each OPSEs.

4.3.3 Standardized Precipitation Index (SPI)

The SPI was used to characterize drought and is based on the evaluation of the probability of precipitation at different timescales (3-, 6-, 12-, 24- and 48-months) (McKee et al., 1993). This index evaluates drought conditions based only on precipitation and has proven to be effective for analyzing wet and dry periods (Lorenzo et al., 2024). The SPI uses only precipitation data to calculate a standardized value that represents the deviation of the precipitation from the long-term average (at least 30 years) for a given location and time-period (Magallanes et al., 2024). The computed SPI values are then classified into categories based on their magnitude, with negative values indicating drier than average conditions and positive values indicating wetter than average conditions (McKee et al, 1993). Table 4.1 displays the categorization of SPI values ranging from “extreme dry” to “extremely wet”, as well as intermediate categories indicating moderate to severe dry or wet conditions.

Table 4.1. Climatic moisture categories for the Standardized Precipitation Index (McKee et al. 1993). A drought event occurs any time the SPI is continuously negative and reaches an intensity of -1.0 or less. The event ends when the SPI becomes positive.

SPI	Climatic moisture categories
2.0 +	extremely wet
1.5 – 1.99	very wet
1.0 – 1.49	moderately wet
- 0.99 to 0.99	near normal
- 1.0 to -1.49	moderately dry
-1.5 to -1.99	Severely dry
- 2.0 or less	Extremely dry

Fot this study, the SPI was computed with the 12-months accumulation period. The use of SPI-12 reflects longterm precipitation anomalies that affect groundwater, streamflow and reservoir storage (WMO, 2012). The drought periods were evaluated with SPI values obtained with the precipitation datasets from CHIRPS and the CanRCM4 model based in the following indicators: a) drought frequency, defined as the number of drought events for a given period and; b) drought duration, the number of months in which SPI values are negative for a drought event, and c) drought intensity corresponds to the cumulative SPI from all events. Thus, the more negative the value, the more intense the drought (Spinoni et al., 2020; Loenzo et al., 2024).

The droughts periods were estimated for the three evaluated 30-yr periods in this study being 1981–2010 representing the reference period; and 2040-2070 and 2071–2100 representing the near and far future. In this study, we used the SPI program from the National Mitigation Drought Center for SPI computation, which is free access (NMDC, 2018).

4.3.4 Understanding of drought concept and adaptation responses in the OPSE Mapimí

Face-to-face semi-structured interviews were conducted between October 2021 and February 2022. For these interviews, only adults were selected who currently live in the OPSE Mapimí or who perform all or part of their economic activities in the OPSE. In this case only adults were consulted, since they could provide information on droughts that had occurred in the past. A survey three sections consisted of a mixture of open and closed questions. In the first section, the participants were asked basic questions on demographic and socioeconomic aspects (i.e. gender, age, education level, occupation, etc). The second section focused on the perception of drought, change in past climate (i. e. precipitation and temperature changes) and if they remembered any particular drought events (preferably the year of occurrence). In the third section, participants were asked if they recalled a drought event and what happened prior, during and after of the drought (adaptation measures). If no drought event or year of occurrence was identified, the interview was terminated. Face-to-face interview data were processed and statistically analyzed using simple descriptive statistics.

4.4. Results

4.4.1 Drought patterns in the recent past

For the OPSE Guadalupe, the difference in SPI evaluated with the CHIRPS and CanRCM4 model data for the historical period (1981-2010) is evident in the frequency of drought events (Fig. 4.2). A high frequency of moderately wet and moderately dry events can be observed with CHIRPS. On the other hand, the results show a low frequency of severely dry events with CHIRPS and a high frequency of severely dry events with the CanRCM4 model. The results show only an extremely dry event with CHIRPS, whereas the CanRCM4 model did not record any dry event.

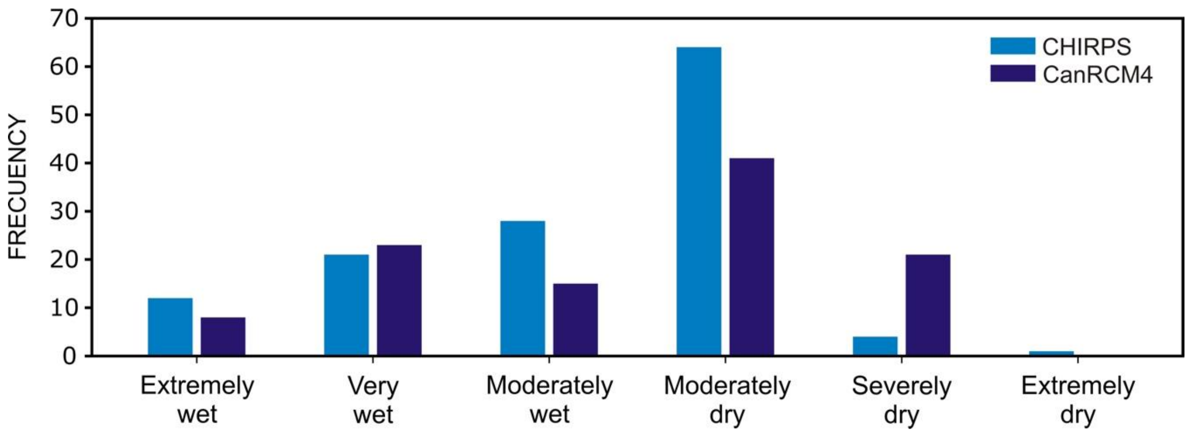


Fig. 4.2. Frecuency of wet and dry events associated with the Social-Ecological Participatory Observatories (OPSE) Guadalupe computed for a 12-months (SPI-12) period for the historical period 1981-2010.

The OPSE Guadalupe experienced three most severe droughts since 1981 (Table 4.2). Considering drought duration, the 2006 – 2009 drought was the longest lasting 47 months for CHIRPS. The average duration of droughts in the OPSE Guadalupe was 32 months for CHIRPS. Considering drought intensity, the 1989-1991 drought was the most severe drought with the lowest SPI value (-2.06) for CHIRPS.

Table 4.2. Characteristics (start and end time), drought duration, and drought intensity) of the three most severe drought events at 12-months time scale for the OPSE Guadalupe.

CHIRPS

Classification	Drought event	Start - End	Drought duration	Intensity
Severely dry	1	February 2002-December 2004	35	-1.79
	2	February 2006-December 2009	47	-1.75
Extremely dry	3	December 1989 - Febrero 1991	15	-2.06

For the OPSE Comcaac (historical period from 1981-2010) a high frequency of moderately, severely and extremely dry events occurred considering the CanRCM4 model (Fig. 4.3). The results show five extremely dry events with the CanRCM4 model, whereas none of these extreme events was recorded with CHIRPS data.

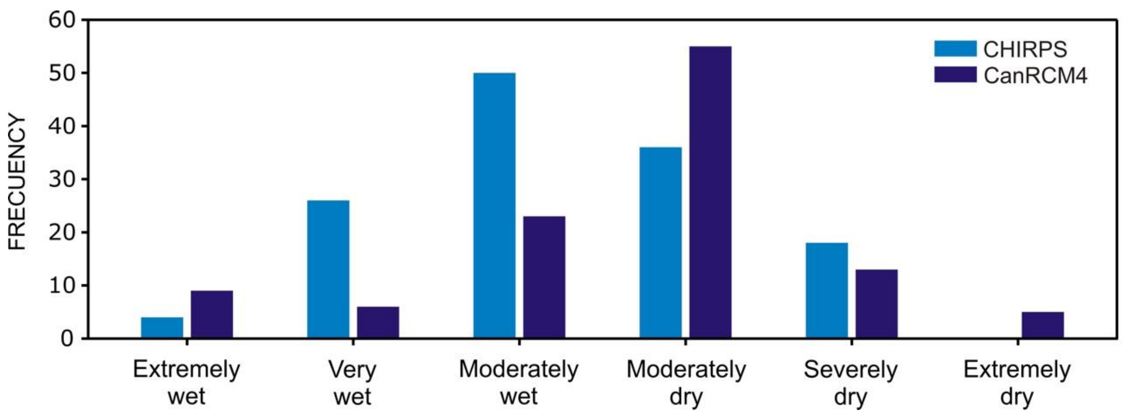


Fig. 4.3. Frecuency of wet and dry events associated with the Social-Ecological Participatory Observatories (OPSE) Comcaac computed for a 12-months (SPI-12) period for the historical period 1981-2010.

The OPSE Comcaac experienced four highly severe droughts between 1981 and 2010 (Table 4.3). According to drought duration, the 1996-1998 drought was the longest event for the 24 months period for CHIRPS. The average duration of drought events in the OPSE Guadalupe was between 15 months for CHIRPS data.

Considering drought intensity, the 2009-2010 drought was the most severe drought with the lowest SPI value (-1.96) for CHIRPS.

Table 4.3. Characteristics (start and end time), drought duration, and drought intensity) of the three most severe drought events at 12-months time scale for the OPSE Comcaac.

CHIRPS				
Classification	**Drought event**	**Start - End**	**Drought duration**	**Intensity**
Severely dry	1	January 1990 - August 1990	8	-1.57
	2	March 1996 - February 1998	24	-1.71
	3	February 2006 - September 2006	8	-1.84
	4	July 2009 - December 2010	18	-1.96

For the OPSE Cuauhtemoc, the difference in SPI evaluated with the CHIRPS and CanRCM4 model data for the historical period (1981-2010) is evident in the frequency of drought events (Fig. 4.4). A high frequency of moderately and severely dry events can be observed with CHIRPS. On the other hand, the results show a high frequency of extremely dry events with the CanRCM4 model.

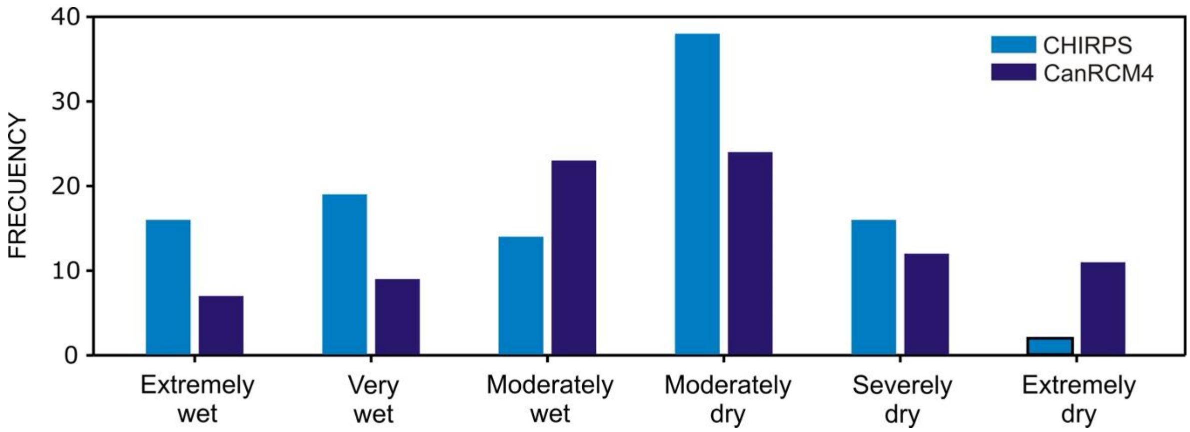


Fig. 4.4. Frecuency of wet and dry events associated with the Social-Ecological Participatory Observatories (OPSE) Cuauhtemoc computed for a 12-months (SPI-12) period for the historical period 1981-2010.

The OPSE Cuauhtemoc experienced three most severe droughts since 1981 (Table 4.4). Considering drought duration, the 2000 – 2004 drought was the longest lasting 47 months for CHIRPS. The average duration of droughts in the OPSE Cuauhtemoc was 27 months for CHIRPS. Considering drought intensity, the 2000-2004 drought was the most severe drought with the lowest SPI value (-2.08) for CHIRPS.

Table 4.4. Characteristics (start and end time), drought duration, and drought intensity) of the three most severe drought events at 12-months time scale for the OPSE Cuauhtemoc.

CHIRPS				
Classification	**Drought event**	**Start - End**	**Drought duration**	**Intensity**
Severely dry	1	October 1982 - July 1984	22	-1.55
	2	August 1995 - July 1996	12	-1.62
Extremely dry	3	September 2000 - July 2004	47	-2.08

For the OPSE Mapimí (historical period from 1981-2010) a high frequency of moderately, severely and extremely dry events occurred considering the CanRCM4 model (Fig. 4.5). The results show 15 extremely dry events with the CanRCM4 model, whereas only two extreme events was recorded with CHIRPS data.

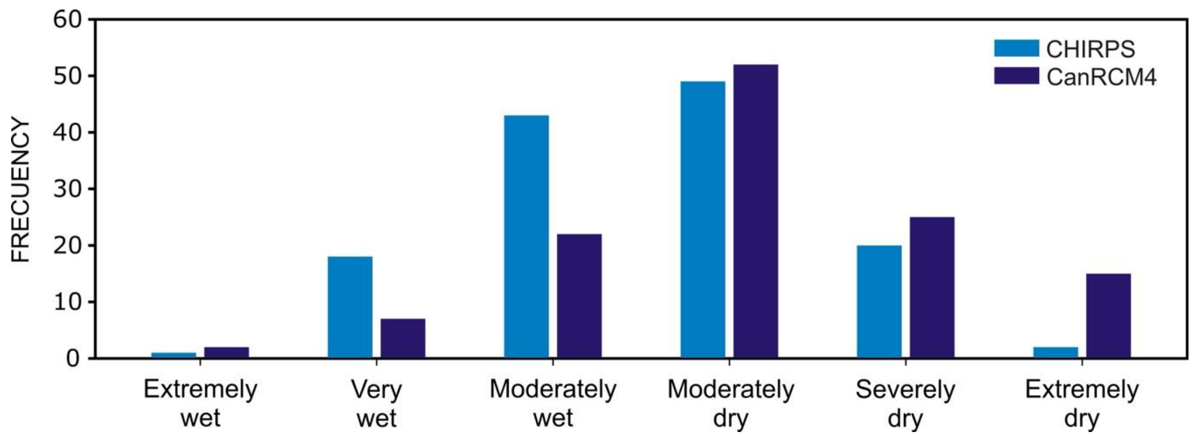


Fig. 4.5. Frecuency of wet and dry events associated with the Social-Ecological Participatory Observatories (OPSE) Mapimi computed for a 12-months (SPI-12) period for the historical period 1981-2010.

The OPSE Mapimi experienced six highly severe droughts between 1981 and 2010 (Table 4.5). According to drought duration, the 1995-1997 drought was the longest event for the 21 months period for CHIRPS. The average duration of drought events in the OPSE Mapimi was between 12 months for CHIRPS data. Considering drought intensity, the 1989-1990 drought was the most severe drought with the lowest SPI value (-2.09) for CHIRPS.

Table 4.5. Characteristics (start and end time), drought duration, and drought intensity) of the three most severe drought events at 12-months time scale for the OPSE Mapimi.

CHIRPS				
Classification	**Drought event**	**Start - End**	**Drought duration**	**Intensity**
Severely dry	1	July 1983 - May 1984	11	-1.56
	2	January 1993 - August 1993	8	-1.88
	3	June 1995 - February 1997	21	-1.92
	4	June 1998 - June 1999	13	-1.84
	5	April 2002 - September 2002	6	-1.53
Extremely dry	6	July 1989 - July 1990	13	-2.09

For the OPSE El Tokio, the difference in SPI evaluated with the CHIRPS and CanRCM4 model data for the historical period (1981-2010) is palpable in the frequency of drought events (Fig. 4.6). A high frequency of moderately wet events and moderately, severely and extreme dry events can be observed with CHIRPS. On the other hand, the results show a high frequency of extremely wet events with the CanRCM4 model.

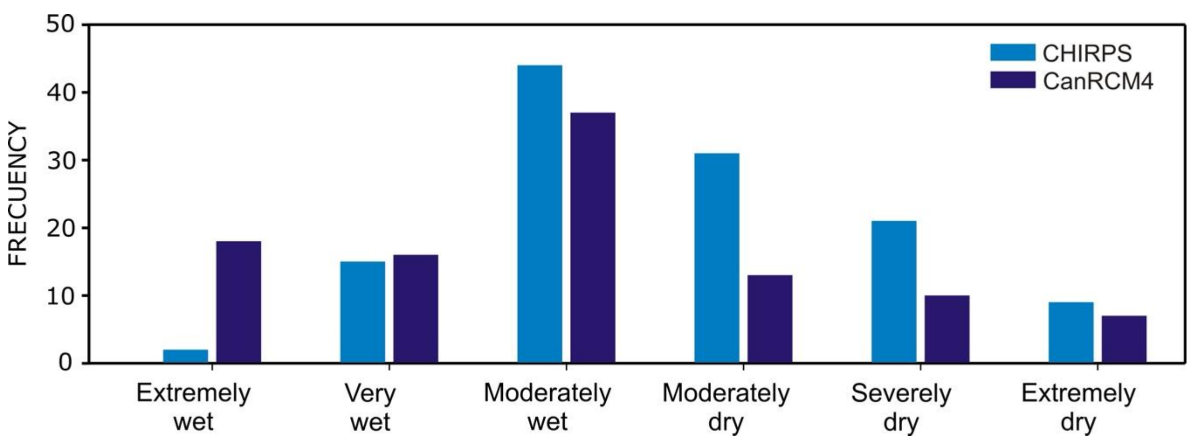


Fig. 4.6. Frecuency of wet and dry events associated with the Social-Ecological Participatory Observatories (OPSE) El Tokio computed for a 12-months (SPI-12) period for the historical period 1981-2010.

The OPSE El Tokio experienced four highly severe droughts between 1981 and 2010 (Table 4.6). According to drought duration, the 1998-2001 drought was the longest event for the 39 months period for CHIRPS. The average duration of drought events in the OPSE Guadalupe was between 16 months for CHIRPS data. Considering drought intensity, the the 1998-2001 drought was the most severe drought with the lowest SPI value (-2.6) for CHIRPS.

Table 4.6. Characteristics (start and end time), drought duration, and drought intensity) of the three most severe drought events at 12-months time scale for the OPSE El Tokio.

CHIRPS				
Classification	**Drought event**	**Start - End**	**Drought duration**	**Intensity**
Severely dry	1	Sempember 1989 - June 1990	10	-1.99
	2	August 1996 - April 1997	9	-1.96
	3	February 2006 - August 2006	7	-1.89
Extremely dry	4	June 1998 - August 2001	39	-2.6

4.4.2 Future drought patterns

To better understand future changes in drought patterns for the 21st century for the region of the OPSEs, changes in the annual precipitation regarding historic records (1981-2010) and two future periods of 30 years each; 2041–2070 (near future) and

2071-2100 (distant future) were analyzed. The annual cycles of precipitation for the historic period were estimated using the historical montly precipitation data from CHIRPS; while the future periods were estimated using the climate simulations (montly precipitation) from CanCMR4 model.

For the OPSE Guadalupe, future annual precipitation cycles are well represented with respect to the historical period, however some differences can be noted in the amount of monthly precipitation (Fig. 4.7.a). For the near (2041-2070) and distant (2071-2100) future periods, the precipitation peaks are projected to change; for instance, the July, August, January and February peaks increase especially in the far future period; however, for the October and November peaks, the precipitation is projected to decrease for both future periods. Considering the historical annual precipitation, an increase in the average annual precipitation is projected for the two future periods, e.g. from 196 mm to 212 mm (near future) and to 251 mm (distant future); i.e. 8 % and 28 % of increase respect to the historic period. Future characteristics of SPI based drought, demarcating that an high frequency of moderately dry events in the near future (2041-2070) and a low frecuency of severely dry and extremely dry events in the distant future (2071-2100) (Fig. 4.7b).

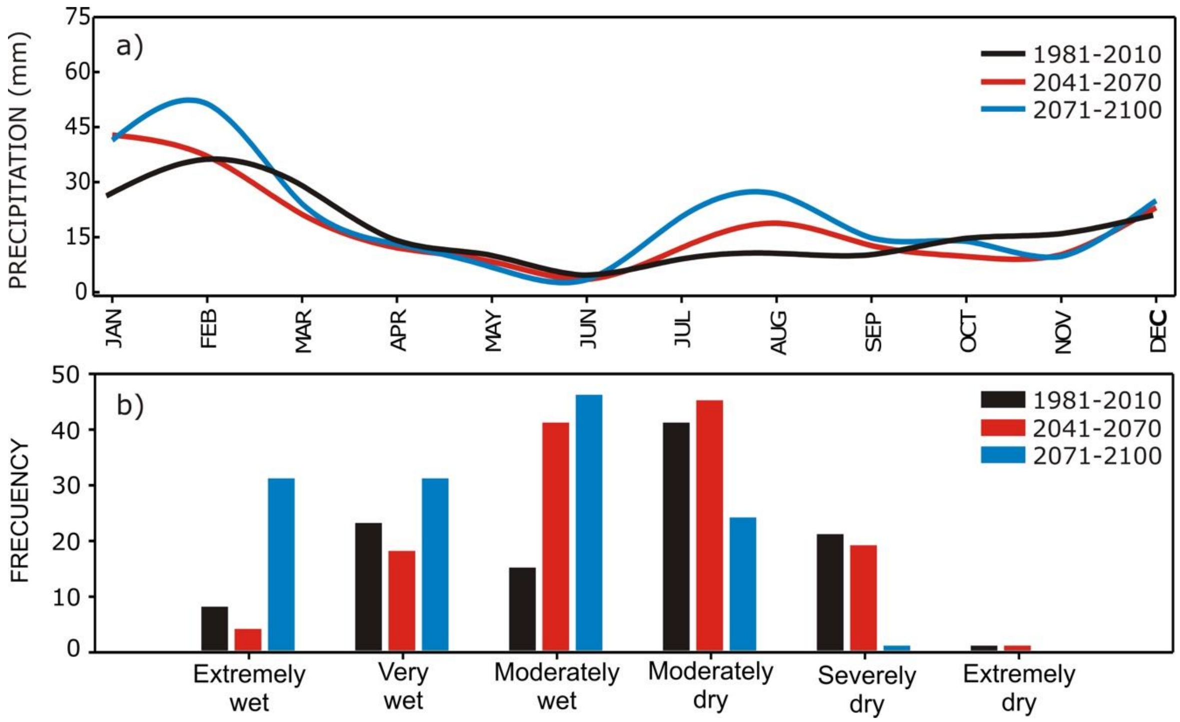


Fig. 4.7. OPSE Guadalupe precipitation and drought patterns; a) annual cycle of precipitation for historic (1981-2010) and future (2041-2070 and 2071-2100) periods; and b) drought frecuency (number of wet and dry events) for the historic and two future periods considering 12-months periods (SPI-12).

The results reveal that over the near future, there will be a maximum drought duration of 24 months with the lowest SPI value of -2.07; while in the distant future there will be a maximum drought duration of 15 months with the lowest SPI value of -1.69. For the OPSE Guadalupe, the average duration of drought events could last from 15 months for the near and far future, while the intensity could be of SPI = -2.0 for the near future and SPI = -1.69 for the far future.

For the OPSE Comcaac, the precipitation peaks are projected to change, the peaks of the July and August months will increase especially in the far future (Fig 4.8a). In general, the results project a increase in the average annual precipitation for both future periods with respect to the historical average precipitation. For example, for the historical period precipitation was 109 mm, while for the near future, it will rise to 117 mm (7 % of increase), and for the far future to 139 mm (27 % of increase). The The climate will be characterized by a high frequency of severely dry and extremely dry events in the near future (2041-2070) and a low frecuency of severely dry and extremely dry events in the far future (2071-2100) (Fig. 4.8b).

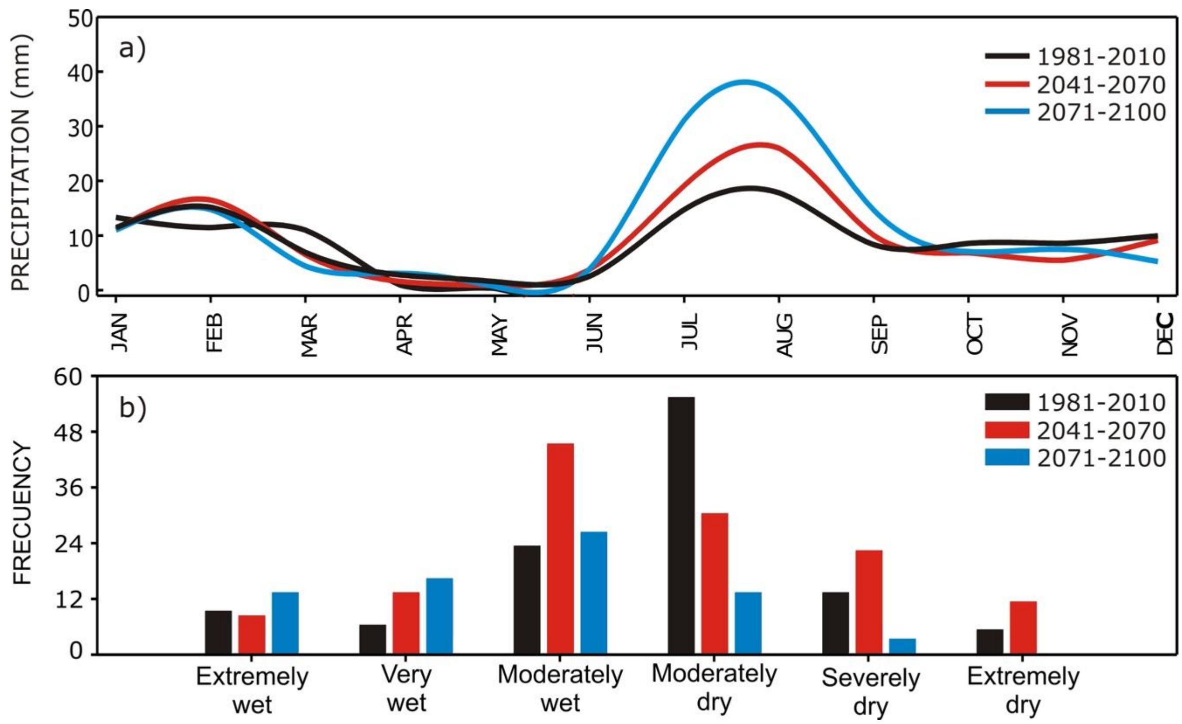


Fig. 4.8. OPSE Comcaac precipitation and drought patterns: a) annual cycle of precipitation associated with the historic (1981-2010) and two future (2041-2070 and 2071-2100) periods, and b) drought frecuency (number of wet and dry events) for the historic and the future periods at 12-months (SPI-12).

With respect to drought duration, the results reveal that over the near future, the maximum drought duration is for 36 months, while that for the far future is for six months. The average duration of drought event in the OPSE Comcaac is for 15 months and five moths for the 2041-2070 and 2071-2100 periods, respectively. According to drought intensity, SPI= -2.76 is the lowest intensity for the near future and SPI= -1.74 for the far future.

For the OPSE Cuauhtemoc, the anual cycle of precipitation projected an increase to the near and distant future considering the months of July, August and September (Fig. 4.9.a). In general, for the OPSE Cuauhtemoc the precipitation projection depicts that the precipitation will gradually decrease in the near future and increase in far the future; the historical average annual precipitation lies at 439 mm, while it decrease to 428 mm in the near future (2 % of diminution), and to 508 mm period in the distant future (16 % of increase). A high frequency of moderately dry events and a low frecuency of severely dry events will occur in the near future (2041-2070). In the far future, the results reveal a low frecuency of moderately and severely dry event, even the results do not project the occurrence of extremely dry events (Fig. 4.9.b).

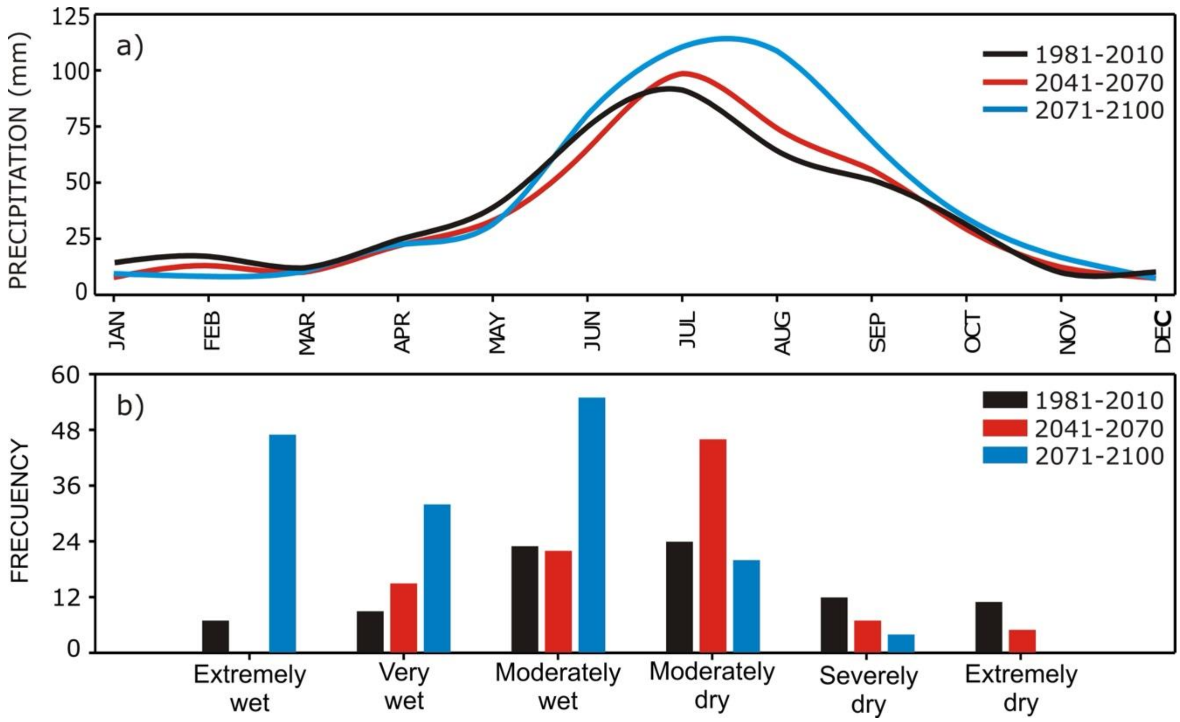


Fig. 4.9. OPSE Cuauhtemoc precipitation and drought patterns: a) annual cycle of precipitation associated with the historic (1981-2010) and two future (2041-2070 and 2071-2100) periods, and b) drought frecuency (number of wet and dry events) for the historic and the future periods at 12-months (SPI-12).

With respect to drought duration, the results project a maximum drought duration of 26 months in the near future (2041-2070) and of 14 months in the far future (2071-2100), while that the average drought duration is from 14 months for both future periods. According to drought intensity, SPI = -2.5 is the lowest intensity for the near future and SPI = -1.86 for the distant future.

For the OPSE Mapimi, future annual precipitation cycles are well represented with respect to the historical period, however some differences can be noted in the amount of monthly precipitation (Fig. 4.10.a). For the near (2041-2070) and distant (2071-2100) future periods, the precipitation peaks are projected to change; for instance, July to September peaks increase especially in the near future period; and June to September peaks, the precipitation is projected to increase in the distan future. Considering the historical annual precipitation, an increase in the average annual precipitation is projected for the two future periods, e.g. from 329 mm to 354 mm (near future) and to 408 mm (distant future); i.e. 8 % and 24 % of increase respect to the historic period. Future characteristics of SPI based drought, demarcating that a low frequency of moderately, severely and extremely dry events in the near future (2041-2070) and distant future (2071-2100) (Fig. 4.10b).

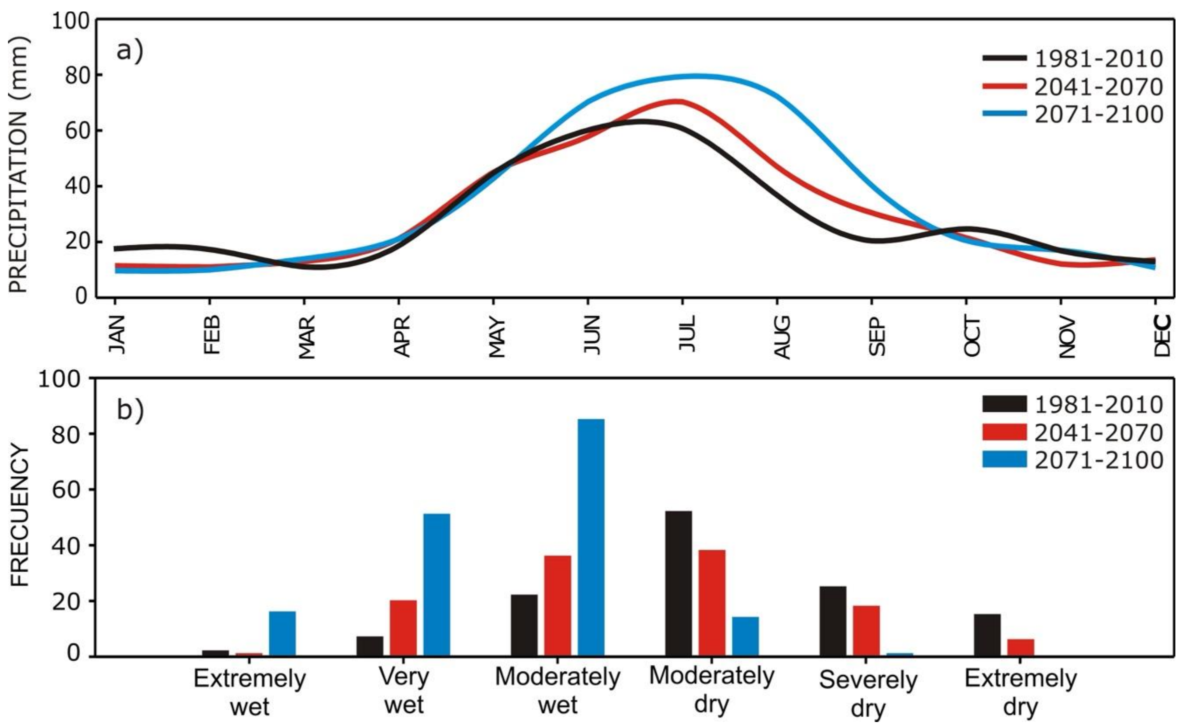


Fig. 4.10. OPSE Mapimi precipitation and drought patterns: a) annual cycle of precipitation associated with the historic (1981-2010) and two future (2041-2070 and 2071-2100) periods, and b) drought frecuency (number of wet and dry events) for the historic and the future periods at 12-months (SPI-12).

The results reveal that over the near future, there will be a maximum drought duration of 14 months with the lowest SPI value of -2.66; while in the distant future there will be a maximum drought duration of nine months with the lowest SPI value of -1.66. For the OPSE Mapimi, the average duration of drought events could last from 10 months for the near future and nine months for the far future, while the intensity could be of SPI = -2.0 for the near future and SPI = -1.66 for the distant future.

For the OPSE El Tokio, the precipitation peaks are projected to change, the peaks of the July and August months will increase especially in the far future, however the peaks of the November, December and January peak months will drecrease in both periods (Fig 4.11a). In general, the results project an decrease in the average annual precipitation for the near future and an increase in the distant future with respect to the historical average precipitation. For example, for the historical period precipitation was 484 mm, while for the near future, it will drop to 446 mm (8 % of decrease), and for the far future to 499 mm (3 % of increase). The climate will be characterized by a high frequency of severely dry and a low frecuency of extremely dry events in the near future (2041-2070) and a low frecuency of severely dry in the far future (2071-2100) (Fig. 4.11b).

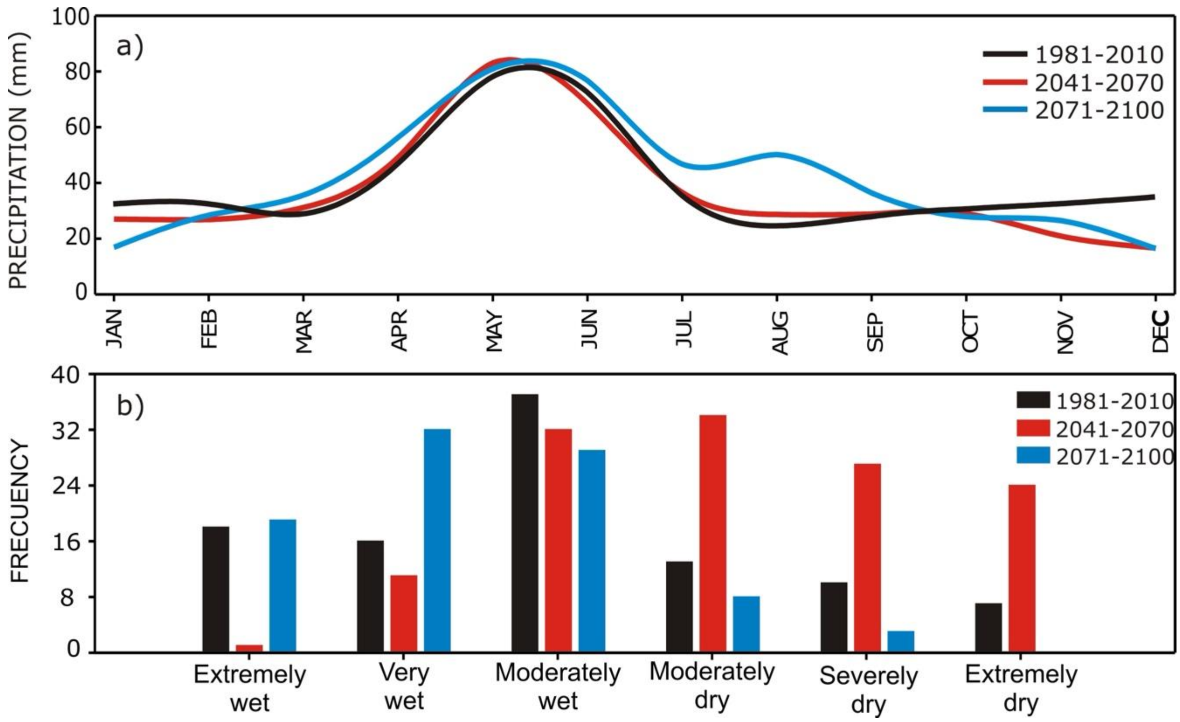


Fig. 4.11. OPSE El Tokio precipitation and drought patterns: a) annual cycle of precipitation associated with the historic (1981-2010) and two future (2041-2070 and 2071-2100) periods, and b) drought frecuency (number of wet and dry events) for the historic and the future periods at 12-months (SPI-12).

The results reveal that over the near future, there will be a maximum drought duration of 61 months with the lowest SPI value of -2.62; while in the distant future there will be a maximum drought duration of 8 months with the lowest SPI value of -1.68. For the OPSE El Tokio, the average duration of drought events could last from 23 months for the near and 8 months for the far future, while the intensity could be of SPI = -2.0 for the near future and SPI = -1.68 for the far future.

4.4.3 Experiences and perceptions of drought shared by local communities associated with the OPSE MapimI

Face-to-face interview sessions were held with xxx members of the local communities aged 51 years (18 to 86 years), with 53% women and 43% men. Considering the level of education, 31% completed elementary school, 31% middle school, 19% high school, and 19% did not attend schools. Among all respondents 22% were engaged in cattle ranching, 19% were homemakers, and 19% worked as environmental promoters and guards, 14% were engaged in ecotourism, 14% were dedicated to salt producer, 8% were engaged as laborers, and 3% did not work. Community members have lived in the area for more than 25 years (36%), 0-5 years (8%), and 5-10 years (6%).

In the face-to-face interview, respondents associated drought mostly with rainfall and vegetation related issues. The majority of the respondents considered drought as no rain (64%), no forage (22%), lack of water (14%) (Table 4.7). Despite of drought being related to a lack of rainfall, six percent of the interviewees associated death of cattle with drought. On the other hand, three percent of the interviewes stated that drought meant more work and economic shorthage.

Table 4.7. Interviewees' definition of drought in the study area (10 responses) for OPSE Mapimí.

Definition	Respondents (N=36)	Percent of respondents	Ranking (n=10)
No rain	23	64 %	1
Lack of water	5	14 %	3

No forage	8	22 %	2
Scarce vegetation	1	3 %	5
Lack of water seasons	1	3 %	5
Land is lonely	1	3 %	7
Death of cattle	2	6 %	4
More work	1	3 %	8
Economic shortage	1	3 %	9
Lean animals	1	3 %	10

With respect to recalling and experiencing drought events in the past, when asked about the last drought or if they had experienced other severe droughts, not all interviewees seemed to remember and only a few were able to mention specific years of drought (Figure 4.12). Only two respodents (aged 67 and 86) were able to remember severe droughts before of 1981. Over 53 percent of the interviewees recalled recent drought years. On the other hand, 1958, 1987, 1990, 2000, and 2022 were mentioned as wet years, which caused flooding in the ejido Laguna de Palomas as part of the OPSE Mapimí.

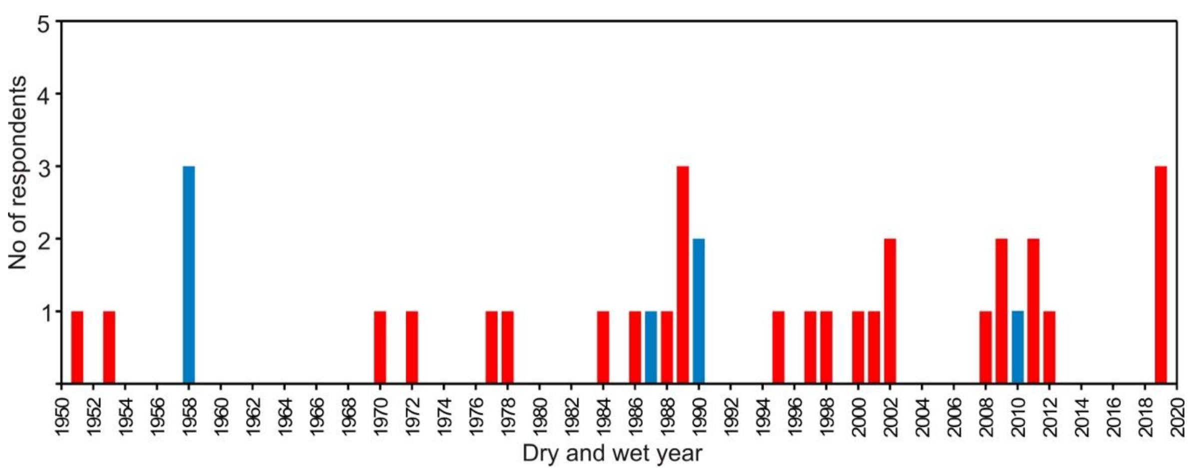


Fig. 4.12 Number of interviewed people remembering past dry and wet years in the region of the OPSE Mapimí (blue bar = wet years, red bar = dry years) for the 1981-2010 historical period.

The participants detected the following changes in climate: there was more rain in the past (31% of the respondents), there was no defined rainy season (23% of the respondents), increased heat (29%), more frequent droughts (3%), and more extreme cold (14%). According to interviewees, the main impacts of a drought event were livestock deaths, low salt production, and migration. The activities that were carried out to minimize the impacts of a drought event and to adapt to the present conditions were: selling some animals to maintain the remaining ones, cutting and burning prickly pear as a source of food, to work on neighboring ranches for complementary income, receiving economic support from relatives, to move water from neighboring communities and migrate (temporarily) to cities. The other sectors (salt producers, ecotourism and environmental promoter and guardians) were supported with temporary employment mainly by government agencies. Finally, mitigation strategies were implemented after a drought event including the acquisition of solar pumps, construction of drinking troughs, improving water conduction and distribution (hose), which were mainly carried out by cattle ranch.

4.5 Discussion

The causal mechanisms of the rainfall distribution patterns in Mexico has been characterized by numerous authors (Cavazos and Hastenrath, 1990; Magaña et al. 2003; Mendez et al., 2008). These studies indicate that annual rainfall increases along a north-south gradient, and secondarily, along a west-east gradient. Precipitation concentrates in the summer, this occurs in the Sonoran Desert (OPSEs Comcaac), and Chihuahua Desert (OPSEs Cuauhtemoc, Mapimi, and El Tokio); in the extreme northwest characterized by Mediterranean climate, winter rainfall dominates (OPSE Guadalupe) (Cavazos and Hastenrath, 1990; Mendez et al., 2008). In the 1981-2010 period, variability in average annual rainfall ranged between 158 mm for the OPSE Comcaac to 388 mm for the OPSE Cuauhtemoc, with different drought patterns considering the OPSE network. Our results indicate that the OPSE territories experienced severe to extreme long-duration droughts (up to 47 months by the OPSEs Guadalupe and Cuauhtemoc), however on average the occurrences of droughts tended to occur in independent periods.

Drought characteristics over Mexico have also been studied at different spatial scales and some studies of this kind have been conducted covering all or part of the area of the OPSEs. Nuñez et al. (2007) analyzed the droughts that occurred in the Chihuahua State between 1970 and 2004 using monthly series of rainfall from weather stations. At the SPI-12 time scale, the most outstanding drought events considering their intensity and duration occurred from 1993 to 1994 and from 2001 to 2004. These results corroborate the findings of this study, where the most severe drought began in September 2000 and lasted for 47 months. De Jesus et al. (2016) evaluated the SPI in Mexico during for the period 1998 to 2013 using the Tropical Rainfall Measuring Mission (TRMM) satellite product 3B42. Their results suggest that the Sonora State experienced the driest conditions during the great drought between 2011 and 2012; however, temporal variability in the SPI was found across different climatic regions. According to our results, the OPSE Comcaac (Sonora) experienced the most severe drought starting in July 2009; it lasted for 19 months.

However, based on the period analyzed, it was not possible to verify when this drought event actually ended.

Identifying the onset and the end of a drought is not an easy task, therefore the end of a drought is not unequivocally defined, as it depends on whether the focus is more on the meteorological aspects (e.g. return to normal precipitation) or impact aspects (recovery of ecosystems and societal impacts) (ECJRC-UNCCD, 2024). In general, some discrepancies among drought event characteristics were observed among OPSEs. For example, the frecuency of dry events in recent decades showed variable results; for the OPSE Comcaac an average of 27 dry events were identified (maximum), for the OPSE Guadalupe and Mapimi an average of 24 dry evens were distinguished, for the OPSE El Tokio an average of 20 dry events were recorded and finally, for the OPSE Cuauhtemoc an average of 19 events were identified (minimum).

The average duration of droughts was of 32 months for the OPSE Guadalupe, 27 months for the OPSE Cuauhtemoc, 16 months for the OPSE El Tokio, 15 months for the OPSE Comcaac while that for the OPSE Mapimi was of 12 months. According to drought intensity, the lowest SPI value for the OPSE El Tokio was -2.6, for the OPSE Mapimi was -2.09, for the OPSE Cuauhtemoc was -2.08, for the Average annual precipitation projections for the regions of the OPSEs presented a different behavior. For the near future (2041-2070), a decrease of 3 % and 8 % is projected for the OPSE Cuauhtemoc and El Tokio, respectively. In contrast, an increase of 7 % is observed for the OPSE Comcaac and of 8 % for the OPSE Guadalupe and Mapimi.

In the far future (2071-2100), an increase of 3 % is projected for the OPSE El Tokio, 16 % for the OPSE Cuauhtemoc, 24 % for the OPSE Mapimi, 27 % for the OPSE Comcaac and 28 % for the OPSE Guadalupe. These results contrast with previous works (Liverman and O'Brien's, 1991; Seager et al. 2009; Magaña et al., 2012), which investigated future precipitation occurrence in Mexico, although the precipitation projections over the country have not always been in agreement.

Initially, different models projected contrasting changes in future precipitation amounts in the country, e. g. Liverman and O'Brien's (1991) concluded that Mexico was likely to be warmer and drier in the future, whichever model was being used; it seemed that potential evaporation would increase, and, in most cases, moisture availability would decrease, even where models projected an increase in precipitation. Other studies indicated a nation-wide negative precipitation trend. Seager et al. (2009) argued that climate experiments indicated that Mexico would experience dryer conditions in the 21st century due to global warming, with the potential convergence of natural and anthropogenic droughts. Magaña et al. (2012) demonstrated that precipitation scenarios project large probabilities of decreases in rainfall over northwestern Mexico, with potential reductions as large as 30%, which correspond to a SPI around −1, i.e. a moderate drought.

Several modeling studies utilizing a high-emissions scenario suggest changes in the North American monsoon by the end of the twenty-first century, with some suggesting a drier monsoon thus reducing seasonal precipitation over vast areas of central and northwestern Mexico (Almazroui et al. 2021), while others project a delayed monsoon (Meyer and Jin 2017). The North American Monsoon (NAM) is responsible for providing approximately 70% of the annual precipitation over portions of northwestern Mexico (Ramos, et al. 2022). Nazarian et al. (2024) define the NAM region to include the states of Baja California Sur, Sonora, Sinaloa, Chihuahua, and Durango; in these states the study areas is located.

To summarize, drought conditions at the 12-month time scale in the near future, presented less frequent events with a decrease in duration for the region of the OPSEs. However, changes were found to be more moderate in terms of duration in the far future, with substantial decreases compared to the historic period. As previously mentioned, these results contrast with past studies predicting a general increase in the number and duration of drought events for the Mexican territory. The most extreme emission scenario, RCP 8.5, produced more severe drought responses with an increase in drought severity throughout the century (Escalante and Nuñez, 2017). Spinoni et al. (2020) evaluated the changes in drought indicators based on climate simulations from the Coordinated Regional Climate Downscaling Experiment (CORDEX) for the period 2071-2100 versus the period 1981-2010. The results identified red spots of future meteorological droughts, that is, areas that show a robust increase in drought frequency and severity, including coastal North America, most of Mexico and northern Central America. Some of these discrepancies may have their origin in using different information sources and periods analyzed to calculate the drought indices, which could influence drought characteristics (Um et al., 2017). It is important to keep in mind that these results were obtained using a single climate model, therefore there is a great uncertainty associated with climate models and our results must be taken with caution. On the other hand, it is recognized that our results present some uncertainty, since meteorological drought is based only on precipitation data; however, there are other variables such as temperature and/or relative humidity, which will be affected perhaps in a different way than projected only with precipitation. In this sense, to refine drought monitoring in the OPSEs, a requirement is spatially and temporally consistent meteorological data (Esquivel et al., 2024). Therefore, improving data consistency will require greater investment in the national meteorological station network, especially to reactivate stations whose long-term records have been interrupted; maintain those currently operating; or even better expand the station network.

The following paragraphs discusses the most relevant findings of the perception and adaptation in the OPSE Mapimi respect of the drought phenomen. The study of community experiences and perceptions is an essential aspect of the local knowledge system on how to face meteorological drought, because it complements scientific understanding with conceptions in peoples' everyday lived experience and well-being (Hulme, 2009). Drought cannot only be understood by scientific facts but also by "popular" concepts, shaped by human experiences particularly among local communities of the OPSE, who depend heavily on precipitation and water availability for their subsistence/survival. We wanted to understand how people are making sense of drought events in their daily lives and how they are able to cope/adapt to it whilst maintaining (and ideally improving) their standards of living. In the OPSE Mapimí, the majority of the interviewees were very much aware of the presence of drought and its intensification was frequently mentioned; this indicates that the severity of the drought described by the literature (Domínguez, 2016; Dobler and Bocco, 2021) has indeed been experienced as such by interviewees.

Pronounced changes in the weather were generally recognised across the respondents (more heat and less rain), if not expressed as “climate change”. Drought was commonly reported as no rain followed by no forage; and overall, our respondents’ perceptions of changes in the ocurrence of precipitation, in particular, had important implications on their economic activities. Some interviewees indicated the years 1989, 1995, 1998, 2001 and 2002 and 2008 as the most relevant drought events. Drought events dating back to the 1950s and 1970s, and as recent as in the year 2019 were highlighted by some interviewees. Drought does not only affect the economy of the OPSE Mapimi; it also influences the ecosystems, the life-support system of people according to the study results.

Local people have a clear understanding of their own capacities and capabilities, embedded within local perceptions and understandings of drought phenoma, but these can be quite different among community members. The cattle ranch sold some animals to maintain the remaining ones or cutting and burning prickly pear as a source of food for livestock. The salt producers and ecotourism guides are usually temporarily employed or are receiving economic support from relatives. Besides these adaptation strategies at household and community level, federal and state level actions have been introduced to address the adverse effects of drought and try to reduce vulnerability before and after a drought event (Dobler and Bocco, 2021). However, the efficacy of these support schemes was questioned by local people because of a lack of continuity, consistency and apparent relevance to individual livelihoods and contexts.

Locally generated information and knowledge provided by local communities, as in this study, is vital to inform adaptation policy and supporting and improving existing actions in a way that considers the specific realities and the physical and geographical conditions of the OPSE Mapimí. For example, paddock rotation and rainfall monitoring have emerged as a strategy being applied to counteract the generalized shortage of forage, reducing the dependence on buying forage in other areas, becoming an adaptation to the current drought conditions. In this context, is necessary a transformation not only of productive sectors, but also of social systems, a transformation that should be targeted as a long-term, sustainable adaptation to a new climatic reality (Spinoni et al., 2020; UNCCD, 2024).

4.6. Conclusions

Drought is a recurring phenomenon in Mexico. The country overall is characterized as especially sensitive to the event. Previous studies have suggested that the arid northern Mexico suffered from several droughts in the last decades and will encounter more severe and intense droughts in the future. This study investigated projected changes in meteorological droughts over the 21st century through the SPI index using simulations from the Canadian Regional Climate Model 4 (CanRCM4) considering the network of Social–Ecological Participatory Observatories along a west–east transect in northern Mexico drylands. Projections of SPI-12 from 2041-

2070 were explored under the concentration scenario RCP 8.5, trying to contribute to the knowledge of droughts over México drylands.

According to the RCP 8.5 scenario a increae in annual precipitation for the OPSE is forecasted. Future climate projections also suggest a decrease in the frequency and duration of drought events by the end of the century. The results obtained in this study have shown some discrepancies among drought event characteristics considering other studies; this can be attributted at the information sources, the period analyzed or even the index considered in the study. On the other hand, it should be noted that the results obtained in this chapter were obtained using only with the precipitation datae and did not analyze projections of potential temperature increases, which would increase evapotranspiration rates and consequently greater aridity. It should also be noted that only one regional circulation model was used in this chapter, so the results should be interpreted with caution. The analysis of drought in the context of climate change requires the use of multiple regional climate models to take into account uncertainties from model imperfections, the geophysical data used to represent land and surface features, the greenhouse gas emissions and scenarios, and certain climate change effects and feedback mechanisms that cannot be predicted in deterministic way (Foley, 2010).

The results of this study are highly relevant because they illustrate a general recognition of drought in the OPSE Mapimi and confirm that people identify drought holistically with impacts on personal and social lives and the productive sectors. It demonstrates that this is a socio-environmental issue, exacerbated by climate change, which affects the entire life-support system of a territory and, therefore, public and private actions should be taken into account to reduce vulnerability and improve adaptation. Efforts should also be made to examine the impacts of drought in urban areas; most of the interviewees included in this study had close connections to rural surroundings, while urban areas that do not have such proximity to rural context may present different impacts.

4.7. References

Alatorre, L. C., Díaz, R. E., Miramontes, S., Bravo, L. C., Sánchez, E., 2014: Spatial and Temporal Evolution of the Static Water Level of the Cuauhtemoc Aquifer during the Years 1973, 1991 and 2000: A Geographical Approach. Journal of Geographic Information System, 6, 572-584, http://dx.doi.org/10.4236/jgis.2014.6504.

Almazroui, M., and Coauthors, 2021: Projected changes in temperature and precipitation over the United States, Central America, and the Caribbean in CMIP6 GCMs. Earth Syst. Environ., 5 (1), 1–24, https://doi.org/10.1007/s41748-021-00199-5.

Baez, G. A. D., Torres, M. M. J., Royo, M. M. H., Kiniryd, J. R., 2018: Climate variability and trends in climate extremes in the priority conservation area El Tokio and adjacent areas in northeastern Mexico. Weather and Climate Extremes 22, 36–47, https://doi.org/10.1016/j.wace.2018.10.001.

Beck, H., Zimmermann, N., McVicar, T. et al. 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Sci Data 5, 180214, https://doi.org/10.1038/sdata.2018.214

Castillo, C. M., Ibáñez, C. L. A., Valdés, J. B., Arteaga, R. R., Vázquez, P. Mario A., 2017: Análisis de sequías meteorológicas en la cuenca del río Fuerte, México. Tecnología y ciencias del agua, 8(1), 35-52. https://doi.org/10.24850/j-tyca-2017-01-03.

Cavazos, T. and Hastenrath, S. 1990. Convection and rainfall over Mexico and their modulation by the Southern Oscillation, Int. J. Climatol. 10 377–386.

CE (Climate Engine). 2025. Cloud Computing of Climate and Remote Sensing Data. Accessed January 15, 2025 Available on line: https://app.climateengine.org/climateEngine

CONAGUA. 2018. Mexico Water Atlas 2014. Mexico: Secretariat of Environment and Natural Resources-National Water Commission, 28–41, 84–95. (in

Spanish) Accessed 10 September 2024. https://files.conagua.gob.mx/conagua/publicaciones/Publicaciones/AAM2018.pdf
De Jesús, A., Breña, N. J. A., Pedrozo, A. A., & Alcocer, Y. V. H. 2016. The use of TRMM 3B42 product for drought monitoring in Mexico. Water, 8(8), 325. https://doi.org/10.3390/w8080325
Di Luca, A., De Elía, R. and Laprise, R. 2012. Potential for added value in precipitation simulated by high-resolution nested regional climate models and observations. Climate Dynamics, 38, 1229–1247. https://doi.org/10.1007/s00382-011-1068-3
Dobler, M. C., Bocco, G., 2021: Social and environmental dimensions of drought in Mexico: An integrative review. International Journal of Disaster Risk Reduction, 55, 102067. https://doi.org/10.1016/j.ijdrr.2021.102067
Domínguez, J. 2016. Revisión histórica de las sequías en México: de la explicación divina a la incorporación de la ciencia. Tecnología y Ciencias del Agua, 7(5), 77-93.
ECJRC-UNCCD (European Commission Joint Research Centre and United Nations Convention to Combat Desertification). 2024. World Drought Atlas. [A. Toreti, D. Tsegai, and L. Rossi Eds], Publications Office of the European Union, Luxembourg, doi:10.2760/3842670, JRC 139691.
EDO (European Drought Observatory). 2025: Standardized Precipitation Index (SPI). Accessed 15 November 2024. Available at: https://drought.emergency.copernicus.eu/data/factsheets/factsheet_spi.pdf
Escalante, S. C., Nuñez, G. P., 2021: Meteorological drought features in northern and northwestern parts of Mexico under different climate change scenarios. Journal of Arid Land, 9(1): 65–75. https://doi.org/10.1007/s40333-016-0022-y
Esquivel, A. G., Huber-Sannwald, E., Reyes, G. V. M., Bravo, P. L. C., Dávila, O. R., Martínez, T. N. and Velázquez, Z. J. A. 2024. Performance Evaluation of Global Precipitation Datasets in Northern Mexico Drylands. J. Appl. Meteor. Climatol., 63, 1545–1558, https://doi.org/10.1175/JAMC-D-23-0227.1.
Faiz, M.A., Liu, D., Fu, Q., Naz, F., Hristova, N., Li, T., et al., 2020: Assessment of dryness conditions according to transitional ecosystem patterns in an extremely cold region of China. Journal of Cleaner Production 255, 120348, https://doi.org/10.1016/j.jclepro.2020.120348
Foley, A. M. 2010. Uncertainty in regional climate modelling: A review, Prog. Physi. Geogr., 34, 647–670, doi:10.1177/0309133310375654

Funk, C., and Coauthors., 2015: The climate hazards infrared precipitation with stations - A new environmental record for monitoring extremes. Scientific Data, 2, https://doi.org/10.1038/sdata.2015.66.

Giddings, L., Soto, M., Rutherford, B. M., & Maarouf, A. 2005. Standardized Precipitation Index Zones for México. Atmósfera, 18(1), 33-56. Accessed 15 March 2025, https://www.scielo.org.mx/pdf/atm/v18n1/v18n1a03.pdf

Gond, S., Gupta, N., Dikshit, P.K.S., Patel, J., 2023: Assessment of drought variability using SPEI under observed and projected climate scenarios over Uttar Pradesh, India. Physics and Chemistry of the Earth 131, 103440, https://doi.org/10.1016/j.pce.2023.103440

Hulme, M. 2009. Why we disagree about climate change: understanding controversy, inaction and opportunity. Cambridge University Press, Cambridge

Huntington, J. L., Hegewisch, K. C., Daudert, B., Morton, C. G., Abatzoglou, J. T., McEvoy, D. J. and Erickson, T., 2017: Climate Engine. Cloud Computing and Visualization of Climate and Remote Sensing Data for Advanced Natural Resource Monitoring and Process Understanding. American Meteorological Society, https://doi.org/10.1175/BAMS-D-15-00324.1.

INEGI (Instituto Nacional de Estadística y Geografía) 2025. Simulador de Flujos de Agua de Cuencas Hidrográficas. Accessed 10 November 2024. https://antares.inegi.org.mx/analisis/red_hidro/siatl/

Lauterio, M. C. L., Huber-Sannwald, E., Hernández, V. S. D., Leyva, A. J. C., Lucatello, S., Martínez, T. N., Mata, P. R. I., Reyes, G. V. M., Seingier, G., 2021. Métodos colectivos para tejer el camino desde la desertificación al desarrollo sostenible: los Observatorios Participativos Socio-Ecológicos. Ecosistemas 30 (3): 2232. https://doi.org/10.7818/ECOS.2232.

Liverman, D., and O'Brien, K. L., 1991. Global warming and climate change in Mexico, Global Environ. Change 1, 351–364. https://doi.org/10.1016/0959-3780(91)90002-B

Lorenzo, M.N., Pereira, H., Alvarez, I., Dias, J. M. 2024. Standardized Precipitation Index (SPI) evolution over the Iberian Peninsula during the 21st century. Atmospheric Research 297, 07132, https://doi.org/10.1016/j.atmosres.2023.107132

Magallanes, Q. R., Galván, T. C.E.; Galván, T. J. I., Gamboa, R. H., Méndez, G. S. d. J., García, D. A. 2024. Auto-Machine-Learning Models for Standardized Precipitation Index Prediction in North–Central Mexico. Climate, 12, 102. https://doi.org/10.3390/cli12070102

Marengo, J. A., Torres, R. R., & Alves, L. M. 201). Drought in Northeast Brazil-past, present, and future. Theoretical and Applied Climatology,129(3–4), 1189–1200. https://doi.org/10.1007/s00704-016-1840-8

Magaña, V., Vázquez, J. L., Pérez, J. L., Pérez, J. B. 2003. Impact of el Niño on precipitation in Mexico, Geofisc. Int. 42 (2003) 313–330.
Magaña, V., Zermeño, D. and Neri, C., 2012. Climate change scenarios and potential impacts on water availability in northern Mexico. Climate Research, 51: 171–184, Available on line: https://typeset.io/pdf/climate-change-scenarios-and-potential-impacts-on-water-3muhvbfew6.pdf
Martinez, T. N., Renteria, V. R. F., 2020: Social Cohesion and Environmental Governance among the Comcaac of Northern Mexico. In: Huber-Sannwald, E., Martínez, T. N., Espejel, I. Lucatello, S., Coppock, D. L., (eds.) Stewardship of Future Drylands and Climate Change in the Global South. Springer International Publishing, India., https://doi.org/10.1007/978-3-030-22464-6
Mendez, G. J., Navar, C. J. de J., Gonzalez, O. V. 2008. Análisis de tendencias de precipitación (1920-2004) en México. Invest. Geog n.65. pp.38-55. Available on line: https://www.scielo.org.mx/pdf/igeo/n65/n65a4.pdf
Meyer, J. D. D., and J. Jin, 2017: The response of future projections of the North American monsoon when combining dynamical downscaling and bias correction of CCSM4 output. Climate Dyn., 49, 433–447, https://doi.org/10.1007/s00382-016-3352-8.
McKee, T. B., Doesken, N. J., Kleist, J., 1993: The relationship of drought frequency and duration to time scales. In: Proceedings of the eighth conference on applied climatology. Anaheim, California, pp. 179–184. Available at: https://www.droughtmanagement.info/literature/AMS_Relationship_Drought_Frequency_Duration_Time_Scales_1993.pdf
MDM (Mexican Drought Monitor), 2014. Standardized Precipitation Index. Available online: https://smn.conagua.gob.mx/es/climatologia/monitor-de-sequia/spi (accessed on 05 mayo 2024)
Mishra, A. K., Singh, V. P., 2010. A review of drought concepts. J. Hydrol. 391, 202–216. https://doi.org/10.1016/j.jhydrol.2010.07.012.
NADM (North American Drought Monitor), 2002. Maps and statistics for the NADM. Available online: https://droughtmonitor.unl.edu/nadm/Home.aspx (accessed on 05 mayo 2024).
Nazarian, R. H., Brizuela, N. G., Matijevic, B. J., Vizzard, J. V., Agostino, C. P., & Lutsko, N. J. (2024). Projected Changes in Mean and Extreme Precipitation over Northern Mexico. Journal of Climate, 37(8), 2405-2422. https://doi.org/10.1175/JCLI-D-23-0390.1
NDMC (National Drought Mitigation Center), 2018. SPI Generator [software]. University of Nebraska–Lincoln. Available online: https://drought.unl.edu/Monitoring/SPI/SPIProgram.aspx

Narchi, N. E., Aguilar, R. L. E., Sánchez, E. J. J., and Waumann, R. D. O. 2015. An ethnomedicinal study of the Seri people; a group of hunter-gatherers and fishers native to the Sonoran Desert. J Ethnobiology Ethnomedicine 11, 62. https://doi.org/10.1186/s13002-015-0045-z

NIDIS (National Integrated Drought Information System), 2024. Drought monitoring, forecasting and planning. Available online: https://www.drought.gov/ (accessed on 05 mayo 2024).

Núñez, L. D., Muñoz, R. C. A., Reyes, G. V. M., Velasco, V. I., Gadsden, E. H. 2007. Characterization of drought at different time scales in Chihuahua, Mexico. Agrociencia 41: 253-262

Osborn, T., J. Barichivich, I. Harris, G. van der Schrier, P. Jones, 2016: Monitoring global drought using the selfcalibrating Palmer drought severity index [in "State of the Climate in 2015"]. Bull. Amer. Meteor. Soc., 97, S32–S36, https://www.ametsoc.net/sotc/StateoftheClimate2015_lowres.pdf.

Ramos, P. O., Adams, D. K., Ochoa, M. C. A., and Quintanar, A. I. 2022: A climatology of mesoscale convective systems in northwest Mexico during the North American monsoon. Atmosphere, 13, 665, https://doi.org/10.3390/atmos13050665.

Riahi K, Krey V, Rao S, Chirkov V, Fischer G, Kolp P, Kindermann G, Nakicenovic N, Rafai P. 2011. RCP-8.5: exploring the consequence of high emission trajectories. Climatic Change. doi: 10.1007/s10584-011-0149-y

Rummukainen, M. 2010. State-of-the-art with regional climate models. Wires climate change, 1 (1) 82-86 p. https://doi.org/10.1002/wcc.8

Salas, M. F., Valdés, R. O. A., Palacios, W. O. M., Márquez, G. A. 2021. Analysis of the Evolution of Drought through SPI and Its Relationship with the Agricultural Sector in the Central Zone of the State of Veracruz, Mexico. Agronomy 2021, 11, 2099. https://doi.org/10.3390/agronomy11112099

Scinocca, J. F., Kharin, V. V., Jiao, Y., Qian, M. W., Lazare, M., Solheim, L.,... & Dugas, B., 2016: Coordinated global and regional climate modeling. Journal of Climate, 29(1), 17-35, http://dx.doi.org/10.1175/JCLI-D-15-0161.s1.

Seager, R., Ting, M., Davis, M., Cane, M., Naik, N., Nakamura, J., Li, C., Cook, E. R., Stahle, D. W. 2009. Mexican drought: an observational modeling and tree ring study of variability and climate change, Atmósfera 22, 1–31.

Seneviratne, S. I., 2012: Historical drought trends revisited. Nature, 491, 338–339, https://doi.org/10.1038/491338a.

SMN (Servicio Meteorológico Nacional) 2025a. Estación meteorológica Agua caliente. Available on line: https://smn.conagua.gob.mx/tools/RESOURCES/Normales_Climatologicas/Mensuales/bc/mes02001.txt

SMN (Servicio Meteorológico Nacional) 2025b. Estación meteorológica Laboratorio del desierto. Available on line: https://smn.conagua.gob.mx/tools/RESOURCES/Normales_Climatologicas/Mensuales/dgo/mes10165.txt

Spinoni, J., Naumann, G., Carrao, H., Barbosa, P., & Vogt, J., 2014. World drought frequency, duration, and severity for 1951-2010. International Journal of Climatology, 34(8), 2792-2804. https://doi.org/10.1002/joc.3875

Spinoni, J., Vogt, J. V., Naumann, G., Barbosa, P., & Dosio, A. 2018. Will drought events become more frequent and severe in Europe? Inter-national Journal of Climatology, 38(4), 1718–1736. https://doi.org/10.1002/joc.5291

Spinoni, J. and Coauthors, 2020: Future global meteorological drought hot spots: a study based on CORDEX data. Journal of Climate, 33(9), 3635-3661. https://doi.org/10.1175/JCLI-D-19-0084.1

Torma, C., Giorgi, F. and Coppola, E. 2015. Added value of regional climate modeling over areas characterized by complex terrain—precipitation over the Alps. Journal of Geophysical Research: Atmospheres, 120, 3957–3972. https://doi.org/10.1002/2014JD022781.

Touma, D., Ashfaq, M., Nayak, M. A., Kao, S-C-., Diffenbaugh, N. S., 2015: Amulti-model and multi-index evaluation of drought characteristics in the 21st century. Journal of Hydrology 526, 196–207, https://doi.org/10.1016/j.jhydrol.2014.12.011

Ukkola, A. M., De Kauwe, M. G., Roderick, M. L., Abramowitz, G., Pitman, A. J. 2020. Robust future changes in meteorological drought in CMIP6 projections despite uncertainty in precipitation. Geophysical Research Letters, 46, e2020GL087820. https://doi.org/10.1029/2020GL087820

Um, M.J., Kim, Y., Park, D., Kim, J., 2017. Effects of different reference periods on drought index (SPEI) estimations from 1901 to 2014. Hydrol. Earth Syst. Sci. 21, 4989–5007. https://doi.org/10.5194/hess-21-4989-2017.

van Vuuren, D. P. and Coauthors, 2011: The representative concentration pathways: An overview. Climatic Change, 109, 5–31, https://doi.org/10.1007/s10584-011-0148-z.

Velázquez, Z. J. A., Dávila, O. R. 2018. Comparing the climate change signal on a mexican basin's hydrology evaluated with global and regional climate simulations. Ingeniería, investigación y tecnología, 19(3), 355-365. https://doi.org/10.22201/fi.25940732e.2018.19n3.030

Velázquez, Z. J. A., 2023: Evaluation of the SPI with high-resolution datasets in historical and future climate in central Mexico. Ingeniería Agrícola y Biosistemas, 15(2), https://doi.org/10.5154/r.inagbi.2023.06.030

Vicente-Serrano, S. M., Quiring, S. M., Pena-Gallardo, M., Yuan, S. S., & Dominguez-Castro, F. 2020. A review of environmental droughts:Increased

risk under global warming? Earth-Science Reviews, 201, 102953. https://doi.org/10.1016/j.earscirev.2019.102953
Wang, B., C. Jin, and J. Liu, 2020: Understanding Future Change of Global Monsoons Projected by CMIP6 Models. J. Climate, 33, 6471–6489, https://doi.org/10.1175/JCLI-D-19-0993.1.
Wilhite, D., 2000. Drought as a natural hazard: concepts and definitions. In: Wilhite, D.A. (Ed.), Droughts: Global Assessment. Routledge, London, pp. 3–18.
WRCC (Western Regional Climate Center), 2016: Standardized Precipitation Index. Available online: https://wrcc.dri.edu/Monitoring/spi_products.php (accessed on 05 mayo 2024).
World Meteorological Organization (WMO). 2012. Standardized precipitation index user guide. World Meteorological Organization. Chair, Publications Board. https://library.wmo.int/doc_num.php?explnum_id=7768
World Meteorological Organization (WMO) 2021. WMO atlas of mortality and economic losses from weather, climate and water extremes (1970–2019).
Zhou, Z., Zhang, L., Chen, J., She, D.,Wang, G., Zhang, Q., et al. 2023. Projecting global drought risk undervarious SSP-RCP scenarios. Earth'sFuture, 11, e2022EF003420. https://doi.org/10.1029/2022EF003420

Chapter 5

---

5. General discussion and conclusions

Drylands are one of the most diverse yet highly vulnerable social–ecological systems of planet Earth (Huber-Sannwald et al., 2012). Aridity and drought patterns cause increasing pressure on land and water resources and are some of the largest global environmental and social change problems and thus are a challenge for science and society (Cherlet et al., 2018). Drylands cover an approximate area of 125.3 million hectares of Mexico, representing approximately 65% of the national territory where over 60% of the total population inhabit these areas. According to the recent publications of the World Atlas of Desertification and the World Drought Atlas, potential solutions to land degradation need to be identified and implemented within the context of local social, economic and political conditions; in addition the complexity of drought risk demands cross-sectoral policies accounting for regional diversity, leveraging local knowledge and promoting community engagement. Therefore, cooperation among sectors and countries (sharing knowledge, data, and best practices) is necessary to achieve drought resilience (Cherlet et al., 2018; ECJRC-UNCCD, 2024).

In this research, our study sites, the Social-ecological participatory observatories (OPSEs) are situated along a west–east transect in northern Mexico's drylands. The OPSEs are a socio-environmental innovation and provide a space for the consolidation of formal and informal alliances for sustainability through placed-based learning communities that share diverse knowledge, technologies, and innovations. As a result of these interactions between the OPSEs, three intertwined main priority issues and/or problems were identified: drought, climate change and water scarcity. Since one of the objectives of the OPSE is to strengthen the co-production of knowledge among scientists, members of the public and private sectors, civil associations, and local communities, the question is at what spatial scale should new knowledge be generated or shared?

In this research, we were interested in analyzing the complex and diverse social-environmental values linked to shared land by a group of stakeholders as a basis for co-defining the spatial boundaries of social-ecological systems, and to analyze the future changes of precipitation and the potential occurrences of droughts considering climate change conditions in the context of the network of the OPSEs in the drylands of northern Mexico. This study we were interested in understanding the diverse valuation of meaningful places by different stakeholder groups coinciding in the OPSE Mapimí. This important integrated understanding of shared land thus have has not been presented in a spatial format. However, mapping of these socio-economic variables that are usually not available in vectorial format (for use in the geographic information system) combined with a series of biophysical variables allowed the spatial delineation of a social-ecological system and the determination of socio-ecological units within this social-ecological system. This delineation is highly flexible in that it permits the updating and re-evaluation of boundaries, as it is based on the perception, intuition, experience, interest, knowledge and judgment of different stakeholder groups highly experienced and knowledgeable about the local and current environmental conditions. This new approach to delineating shared land may offer new opportunities for decision-making in spatial contexts.

How does this spatial delimitation contribute to achieving, for example a socio-ecological governance within the OPSEs? The delineation of spatial boundaries of a SEs and governance are interconnected because defining the boundaries of an SES is a critical first step in effective governance, since the way in which the geographic space of a system is defined directly influences how resources, political decisions, and the participation of the multiple stakeholders involved are managed. On other hand, it is recognized that the spatial delimitation can generate challenges in terms of coordination between different levels of governance. For example, if ecological boundaries do not coincide with administrative or political boundaries, conflicts of interest, competencies, or duplication of efforts between government entities may arise. However, this spatial delimitation can also be a opportunity for that the communities to participate in the governance of the socio-ecological system.

When the boundaries of a system are clear and understandable to local actors, a sense of ownership and responsibility is more likely to be generated. Although this sense of ownership was perceived in the OPSE Mapimí, interactions between actors should be strengthened. In this sense, the socio-ecological units proposed in this study can influence the configuration of actors involved in governance. A smaller socio-ecological system in form of SEU might involve primarily local actors, such as communities, local governments, and social organizations. In contrast, a larger system, such as a watershed that crosses several regions, requires more complex governance, with the participation of actors at the regional, national, and even international levels. Further research should seek to complement and contrast these results. An important consideration for future investigation should be sample's size and composition (inclusion of young people) and more stakeholder groups. Other criterion could be the geographic context of basin, for example, the OPSE Cuauhtémoc and the OPSE Guadalupe facilitate the water governance from a water perspective, but not from an administrative perspective, because the basin is contained by several municipalities.

This study also examined how the rainfall gauge network in Mexico's drylands that is highly heterogeneously distributed and frequently with incomplete datasets can be compensated by information derived from global precipitation datasets. Based on the performance of five global precipitation datasets, we suggest using CHIRPS and AgERA5 to fill gaps of observational rain gauge information. CHIRPS combines satellite precipitation measurements and ground station data to produce precipitation time series and provides meteorological data for the period from 1981 to the present, while AgERA5 is based on global reanalysis and provides meteorological data for the period from 1979 to the present, the dataset is updated every day, and it is close to real time.

However, to refine extreme events monitoring and forecasting capabilities in Mexico, like droughts; a first requirement is spatially and temporally consistent observed meteorological data. Some efforts as the National Institute for Forestry, Agriculture, and Livestock Research (INIFAP: Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias) have developed a network of automated weather stations, however some studies have detected delays in sending information, damaged sensors and lack of maintenance, which affect the quality of the information collected (Ramos et al., 2018). Therefore, improving data consistency will require greater investment in the national meteorological station network, especially to reactivate stations whose long-term records were interrupted; maintain those currently operating; or even better expand the station network. The existence of automated climatological stations is also recognized, but some of them belong to the private sector, so access to this information is generally restricted.

Although there are OPSEs that have climatological stations in operation, their records can be complemented with precipitation data estimated at a global scale, if there are periods with no data. One way to contribute to the usefulness of these databases within the OPSEs is through the socialization of the existence of this type of information. However, the social feedback process of this type of database should be explored, for example, a characterization of wet and dry events can be validated based on local perception and direct observations that local communities have been able to identify over time. This validation of information can be done through the congruence between events observed by people and those estimated through data series.

This study allowed the examination of the occurrence (frequency, severity and duration) of historical (1981-2010) and future (2041-2100) droughts at time scale of 12 months over the OPSE network using the Standardized Precipitation Index (SPI).

Likewise, the perception of the concept of drought and the mitigation and adaptation measures were analyzed in the OPSE Mapimí. Results of this analysis suggest the average annual precipitation projections over the OPSEs presented a different behavior. In the near (2041-2070) and far (2071-21000) future, a decrease in the average annual precipitation is projected for the OPSE Guadalupe and Comcaác. While an increase in the average annual precipitation is projected for the OPSE Cuauhtémoc, Mapimí and El Tokio in the near and far future. In general, drought conditions at the 12-month time scale in the near future presented less frequent events with a decrease in duration for the OPSE network. As previously mentioned in Chapter 3, these results contrast with past studies predicting a general increase in the number and duration of drought events for the Mexican territory, therefore there is a great uncertainty associated with climate models and our results must be taken with caution.

In general, drought conditions at the 12-month time scale for the near future suggested less frequent events with a decrease in duration and intensity considering the drylands areas related to OPSE. In the OPSE Mapimí, the drought concept is mostly linked to rainfall (no rain) and vegetation (no forage) related issues. The years 1951, 1953, 1970, 1972, 1977, 1978, 1984, 1986, 1988, 1989, 1990, 1995, 1997, 1998, 2001, 2002, 2008, 2011, 2012 and 2019 were identified as years with the most relevant drought events since they affected their livelihoods. The years 1958, 1987, 1990 and 2010 were identified as the wettest years, causing flooding in the ejido Laguna de Palomas. These dry and wet events coincided with the monthly precipitation data used in this study and the literature (Domínguez et al., 2016).

More research is needed to understand multi-stakeholder perception of drought and its socio-cultural impacts in the context of a changing climate in the OPSEs network. Further research should seek to complement these results. Future investigation should consider a greater sample size and include a greater diversity of demographic aspects (members of different generations and gender); in addition, the perception of drought by people in urban areas should be considered.

This research makes an important contribution by addressing some of the issues more important in the study of socio-ecological systems: the diversity of spatially explicit information (social, economic, ecological); the diversity of scale; the availability or not of the social-ecological information; and the integration of qualitative and quantitative information. One of the innovations of this research is that the process promotes an exchange of information (scientific and non-scientific) and is approached from two different epistemological perspectives: a positivist one, based on observation and measurement (e.g., relief morphometry, land use/cover, precipitation, among others) and a phenomenological one, based mainly on people's experiences (mapping of significant places from perceptions/valuations of space by multiple sectors and the perception of the concept of drought), therefore, this research represents a transferable and replicable approach.

Finally, in this research, it is recognized that our study sites, the OPSEs, have facilitated and promoted the exchange of knowledge among multiple stakeholders (academia, government, civil associations, local communities), which has allowed the creation and implementation of thematic learning communities (CAT in Spanish).

The creation of the CATs depends on OPSE's main socioeconomic activities and the participation of the different sectoral groups. These learning communities aim to generate, share and apply knowledge related to problems defined collectively in the region-specific. For example, in the Mapimí OPSE there are CATs for livestock, water quality and quantity, salt producers, ecotourism, and wildlife, soil and vegetation monitoring (https://opsemapimi.risza.mx/). At OPSE Cuauhtémoc, there is a CAT denomitated watershed council, agriculture and geospatial analysis (https://opsecuauhtemoc.risza.mx/). Given that each OPSE has diversity in terms of socioeconomic conditions and sectors involved, progress in the formation and operation of the CATs has also been different. However, the success of these CATs could lie in a genuine appropriation of the OPSE objectives by the sectors involved, allowing for active participation in knowledge co-production processes, as well as in their diffusion and respective application.

5.1 References

Cherlet, M., Hutchinson, C., Reynolds, J., Sommer, S., von Maltitz, G., 2018. World Atlas of Desertification. Third ed. Publication Office of the European Union, Luxembourg https://doi.org/10.2760/9205

Domínguez, J. 2016. Revisión histórica de las sequías en México: de la explicación divina a la incorporación de la ciencia. Tecnología y ciencias del agua, 7(5), 77-93. Available at: https://www.scielo.org.mx/pdf/tca/v7n5/2007-2422-tca-7-05-00077.pdf

ECJRC-UNCCD (European Commission Joint Research Centre and United Nations Convention to Combat Desertification). 2024. World Drought Atlas. [A. Toreti, D. Tsegai, and L. Rossi Eds], Publications Office of the European Union, Luxembourg, doi:10.2760/3842670, JRC 139691.

Huber-Sannwald, E., Ribeiro, P. M., Arredondo, M. J. T., Braasch, M., Martínez, P. R. M., de Alba, V. J. G., Monzalvo, S. K. 2012. Navigating challenges and opportunities of land degradation and sustainable livelihood development in

dryland social–ecological systems: a case study from MexicoPhil. Trans. R. Soc. B3673158–177 http://doi.org/10.1098/rstb.2011.0349
Ramos, C. C. M., Almeyda, L. I. H., Granados, R. L. D., Molina, M. R., Emilia Raquel Pérez, E. E. R. 2018. Metodología para el diagnóstico de la red de estaciones agroclimatológicas automatizadas en el estado de Nuevo León, México. Acta agrícola y pecuaria, 4 (3): 108-, https://doi.org/10.30973/aap/2018.4.3/5

Appendix

Chapter 2

Table 2.1S Grouping of 12 land use and vegetation classes, synthesized from the large number of classes contained in the original INEGI thematic layer.

Grouped class	Original classification	Code (INEGI, 2018)
Irrigated agriculture	Annual moisture agriculture	HA
	Annual irrigated agriculture	RA
	Annual and permanent irrigated agriculture	RAP
	Annual and semi-permanent irrigated agriculture	RAS
	Permanent irrigated agriculture	RP
	Semi-permanent irrigated agriculture	RS
	Semi-permanent and permanent irrigated agriculture	RSP
Rainfed agriculture	Annual rainfed agriculture	TA
	Permanent rainfed agriculture	TP
	Semi-permanent rainfed agriculture	TS
Water bodies	Water bodies	H2O
No apparent vegetation	No apparent vegetation	DV
	Area devoid of vegetation	ADV
Pine-oak-tascate forest	Oak forest	BQ
	Oak-pine forest	BQP
	Gallery forest	BG
	Oyamel forest	BA
	Pine forest	BP
	Pine-oak forest	BPQ
	Tascate forest	BJ
	Secondary arboreal secondary vegetation of oak forest	VSA/BQP
	Secondary arboreal secondary vegetation of oak-pine forest	VSA/BQP
	Secondary arboreal vegetation of pine-oak forest	VSA/BPQ
	Secondary shrubby vegetation of oak forest	VSa/BQ
	Secondary shrub vegetation of oak-pine forest	VSa/BQP)
	Secondary shrub vegetation of gallery forest	VSa/BG
	Secondary shrub vegetation of pine forest	VSa/BP
	Secondary shrub vegetation of pine-oak forest	VSa/BPQ
	Secondary shrub vegetation of tascate forest	VSa/BJ

Mesquite forest	Mesquite forest	MK
	Xerophytic mesquital	MKX
	Secondary arboreal vegetation of mesquite	VSA/MK
	Secondary shrub vegetation of mesquite	VSa/MK
Chaparral	Chaparral	ML
Scrub desert	Crassicule scrub	MC
	Microphilous desert scrub	MDM
	Rosetophytic desert scrub	MDR
	Sub-montane scrub	MSM
	Secondary shrub vegetation of microphilous desert scrub	VSa/MDM
	Secondary shrub vegetation of rosetophytic desert scrub	VSa/MDR
	Secondary shrub vegetation of submontane scrubland	VSa/MSM
Grassland	Halophytic grassland	PH
	Induced grassland	PI
	Natural grassland	PN
	Secondary shrub vegetation of halophytic grasslands	VSa/PH
	secondary shrub vegetation of natural grasslands	VSa/PN
Urban area	Urban area	AH
Sandy deserts vegetation	Sandy desert vegetation	VD
	Gallery vegetation	VG
	Shrubby secondary vegetation of sandy deserts	VSA/VD
Gypsophilous Halophilic vegetation	Gypsophilous vegetation	VY
	Halophilic xerophytic vegetation	VH
	Secondary shrub vegetation of sandy deserts	VSa/VD
	Secondary shrub vegetation of halophytic xerophilic vegetation	VSa/VH

Table 2.2S Example of fact sheet of socio-ecological units. This information is additional to the one described in Table 2.2.

SHEET DESCRIPTIVE

Social-environmental unit	78	Landscape type:
Area (Ha)	1267.00	Transformed
Municipality	Mapimi-Tlahualilo	
Ejido	La flor	
ATTRIBUTE	CRITERIA	DESCRIPTION
1. ABIOTIC FACTORS		
1.1 Geomoporhology	Hilly plain	
1.1.1 Vertical dissection value	16 < VD < 40	
1.2 Basin	A. La india - L. Palomas	
1.2.1 Sub-basin	Laguna de Palomas	
1.3. Land use and vegetation	Gypsophilus-Haphytic vegetation	
1.4 Aquifer	Ceballos	
1.4.1 State	Durango	
1.4.2 ID	1023	
1.4.3 Hydrologic region	Cuencas centrales del norte	
1.4.4 Disponibility	Unavailable	
1.4.5 Decree	September 2020	
1.5 Climate	Arid semi-warm	
1.5.1 Code	BWhw	
1.6 Soil type	Calcisol	
1.6.1 Second type	Regosol	
1.6.2 Textural class	2	
1.6.3 Textura	medium	
1.6.4 Code	Clsoszn+Rgca/2	
1.7 Soil degradation	Wind erosion	
1.7.1 Degree	Moderate	
1.7.2 Source	Overgrazing	
1.8 Geology	Sedimentary	
1.8.1 Type	Conglomerate	
1.8.2 Era	Cenozoic	
1.8.3 Sub-system	Neogene	
1.9 Hydrology		
1.9.1 Rivers	presence/absence	absence
1.9.2 Stream	presence/absence	Eventual presence
1.9.3 Water bodies	presence/absence	Eventual presence
2. SOCIOECONOMIC FACTORS		

2.1 Municipality	Mapimi - Tlahualilo	
2.2 Land tenure	Ejido	
2.2.1 Name	La flor	
2.3. State	Durango	
2.4 Roads	presence/absence	presence
2.5 Social-envrionmental signifcance	Esthetic	
	Economic	
	Enviormnetal quality	
	Health	
	Heritage	
	Home	
	Learning	
	Reccreation	
	Social	
	Spiritual	
	Subsistence	
3. REGIONALIZATIONS		
3.1 Important bird area	Mapimi	
3.2 Priority terrestrial sites	Medium	
3.3 Priority restoration sites	Extreme	
3.3.1 Code	2904	
3.4 Priority terrestrial region	Mapimi	
3.5 Administrative hydrologic region	Mapimi	
4.6 Physiographic province	Bolson de Mapimi	

Table 2.3S Distribution of all meaningful places sorted by number of mentions (frequency) and selected category.

	Meaningful place	Mentions	Classificación	Categorie
1	Ceballos	35	Population center	9
2	La flor	30	Population center	10
3	Reserva	28	wide area	7
4	Dunas	23	wide area	3
5	Jimenez	21	Population center	6
6	Quimicas del rey	21	Population center	4
7	Torreon	21	Population center	5
8	Laguna de Palomas	19	Area	6
9	Estacion Carrillo	18	Population center	6
10	Granja Morelos	18	wide area	3
11	La vega	18	wide area	4
12	Arenales	17	wide area	3
13	Los remedios	17	site	3
14	Escalon	16	Population center	5
15	Gomez Palacio	14	Population center	5
16	San Jose Alamos	14	site	2
17	Bodega L Palomas	13	site	3
18	Ejido soledad	12	wide area	2
19	El tanque L Palomas	12	site	6
20	Planillas	12	wide area	4
21	Sierra la campana	12	wide area	1
22	El Bordo Palomas	11	wide area	1
23	Carrillo viejo	11	wide area	2
24	Cerro blanco	11	wide area	2
25	Delicias, Chih	11	Population center	1
26	El 80 Palomas	11	wide area	1
27	El invernadero	11	site	1
131	Narices de Urias	4	wide area	2
132	Pinturas rupestres	4	site	2
133	Potrero el estanque	4	wide area	1
134	Potrero la Pila	4	wide area	1
135	Potreros La flor	4	wide area	2
136	Presón barbacoa	4	wide area	1
137	Providencia	4	Population center	1
138	San isidro	4	wide area	1
139	Semillero Guadalupe	4	wide area	2
140	Semillero La flor	4	wide area	2
141	Veracruz	4	Population center	1
142	Zona del silencio	4	wide area	2
143	Bebederos	3	site	1
144	Cerro del marrano	3	wide area	1
145	Cerro la calavera	3	wide area	2
146	Colonia ganadera	3	wide area	1
147	Cuatrocienegas	3	Population center	4
148	Cuauhtemoc	3	Population center	2
149	Cuerpos de agua	3	wide area	1
150	EJ San Ignacio	3	wide area	2
151	Ej Vicente guerrero	3	wide area	1
152	El tanque 1	3	wide area	3
153	Guadalupe - El pujo	3	Population center	2
154	Houston Texas	3	Population center	1
155	La casa	3	site	2
156	La granja	3	Population center	1
157	La zanja	3	wide area	1

28	El Kiosko Palomas	11	site	1
29	El preson Palomas	11	wide area	1
30	Entrada Ejido Pal	11	site	1
31	Iglesia Palomas	11	site	1
32	La esperanza	11	Population center	1
33	La estacion	11	site	1
34	Las glorias	11	Population center	2
35	La salida	11	site	1
36	Laboratorio del desierto	11	site	7
37	Laguna de los patos	11	Area	2
38	Liberacion	11	Population center	4
39	Loma del consuelo	11	wide area	1
40	Loma prieta	11	wide area	2
41	Lomas de las borregas	11	wide area	1
42	Los barrios	11	Population center	1
43	Los campos	11	wide area	1
44	Panteon L Palomas	11	wide area	2
45	Parral	11	Population center	1
46	Preson L Palomas	11	wide area	1
47	Preson del aniego	11	wide area	2
48	Preson del marrano	11	wide area	2
49	Ranchos meloneros	11	wide area	1
50	San Francisco	11	Population center	1
51	San Jorge	11	wide area	1
52	Sitios de monitoreo	11	wide area	1
53	El centro L Plomas	11	wide area	1
54	Via del tren	11	wide area	3

158	Lomas de las piedras	3	wide area	2
159	Mapimi	3	Population center	2
160	Monclova	3	Population center	2
161	Pastizales	3	wide area	2
162	Piedras negras	3	Population center	1
163	San Jose del centro	3	Population center	2
164	Sierra Mojada	3	wide area	2
165	Zona de pastizal	3	wide area	3
166	Las playas del bolson	3	wide area	1
167	Puntas de flecha	3	site	1
168	Sitios de peyote	3	site	2
169	Zonas de cultivo	3	wide area	2
170	Toulouse	3	Population center	2
171	Zonas de amortiguamiento	3	wide area	1
172	Rayas de leopardo vege	3	wide area	1
173	Explotacion de metales	3	wide area	1
174	Montpellier	3	Population center	2
175	Ej Tlahualilo	3	Population center	2
176	CIMAV Chihuahua	3	site	2
177	Brechas	2	site	1
178	Chihuahua	2	Population center	2
179	Ciudad Juarez	2	Population center	3
180	Colonia d tortugas	2	site	1
181	Corrales de piedra	2	site	1
182	Cuenca San Ignacio	2	wide area	1
183	El casco	2	wide area	1
184	El macho CONANP	2	site	1

55	Zona nucleo	11	wide area	2	185	Flor - Soledad	2	wide area	1
56	Preson de San Carlos	9	wide area	5	186	La estrella	2	Population center	1
57	Preson san ignacio	9	wide area	5	187	Las lolas Flor	2		1
58	Cerro de la cruz	8	wide area	4	188	Loma de los pendejos	2		1
59	Durango	8	Population center	3	189	Los cajones	2	wide area	2
60	Espinazo del diablo	8	wide area	3	190	Media gorda	2	wide area	2
61	La escondida	8	site	4	191	Pinabete La flor	2	site	2
62	Lerdo	8	Population center	6	192	Pocitos de los padres	2	site	3
63	Rancherias	8	site	3	193	PP La Pila	2	wide area	1
64	Cerro bola	7	wide area	4	194	Preson de los caballos	2	wide area	1
65	Hacienda Las Lilas	7	wide area	1	195	Preson de los padres	2	wide area	3
66	Las marias	7	Population center	2	196	Preson el laguillo	2	wide area	2
67	San Ignacio	7	site	4	197	Preson el tapado	2	wide area	2
68	Sierra de banderas	7	wide area	3	198	Reserva subterranea	2	wide area	1
69	Venado gacho	7	wide area	4	199	San Jose de Madero	2	Population center	2
70	Autopista	6	wide area	3	200	Sierra calcarea	2	wide area	1
71	Bermejillo	6	Population center	4	201	Sierra del diablo Chih	2	wide area	1
72	Cerro corona	6	wide area	3	202	Sierra Tlahualilo	2	wide area	1
73	Cerro san ignacio	6	wide area	4	203	Sitio del aguila	2	site	1
74	Cerros colorados	6	wide area	3	204	Sitios LTER	2	site	1
75	Preson la becerra	6	wide area	2	205	Soledad	2	Population center	1
76	Acuifero Ceballos	5	wide area	3	206	Tlahualilo	2	Population center	1
77	Acuifero Escalon	5	wide area	3	207	Tortugas	2	wide area	1
78	Acuifero Tlahualilo	5	wide area	3	208	Varillas magneticas	2	site	2
79	Cerro amarillo	5	wide area	1	209	Zona de mogotes	2	wide area	1
80	Cerro colorado	5	wide area	3	210	Zonas de biocostra	2	wide area	1
81	Cerro cuevas	5	wide area	1	211	Zonas de sporobolus	2	wide area	1

82	Cerro tortuga	5	wide area	2	212	Arboles petrificados	1	site	2
83	Cuenca India-Palomas	5	wide area	2	213	Area concentrada de tortugas	1	wide area	1
84	Dunas de cuarzo	5	wide area	2	214	Camino al ejido	1	wide area	1
85	Ejido la flor	5	wide area	2	215	Cañas	1	wide area	1
86	El divisadero	5	wide area	1	216	Cañon de Fdz	1	wide area	1
87	El mono	5	wide area	2	217	Casa de Cita	1	site	2
88	El quemado	5	wide area	1	218	Casas de los alamos	1	site	1
89	Iglesia tortugas	5	site	1	219	Cementerio las lilas	1	site	1
90	La azufrera	5	wide area	1	220	Cerrito prieto	1	wide area	1
91	Las tinajas	5	wide area	2	221	Cerros alamos	1	wide area	1
92	Lomas el canelo	5	wide area	1	222	Cuadrante	1	wide area	1
93	Lomas Fdz	5	wide area	2	223	Dunas de Samalayuca	1	wide area	1
94	Ojo de agua	5	site	5	224	Ganado alamos	1	site	1
95	Pastizal	5	wide area	2	225	Gimbalete	1	wide area	5
96	Pastizal ejido	5	wide area	1	226	Guadalupe	1	wide area	1
97	Picoterio	5	site	1	227	La boquilla	1	site	1
98	Potrero la espuela	5	wide area	1	228	La pila soledad	1	site	1
99	Potrero sin nombre	5	wide area	1	229	La presa soledad	1	wide area	1
100	PP Guadalupe	5	Population center	1	230	Lechuza campanario	1	site	1
101	Presón de la casa	5	wide area	2	231	Loma alta	1	wide area	1
102	Presón los dos amigos	5	wide area	2	232	Loma blanca	1	wide area	1
103	San Carlos	5	wide area	2	233	Lomas soledad	1	wide area	3
104	Sierra de marmol	5	wide area	1	234	Lomas de la casa	1	wide area	2
105	Tierra blanca	5	wide area	2	235	Los bebederos	1	site	2
106	Torrecillas	5	wide area	2	236	Los burros	1	site	1
107	Zona exclusion	5	wide area	1	237	Lotes productivos	1	wide area	2
108	Zona serrana	5	wide area	1	238	New Mexico	1	Population center	1
109	Zonas de sueda	5	wide area	2	239	Noria soledad	1	site	1

110	Area de exclusion	4	wide area	1
111	Arroyo la india	4	wide area	3
112	Buendia	4	wide area	1
113	Cerro apartado	4	wide area	2
114	Cuadrante La flor	4	wide area	2
115	Ejidos	4	wide area	1
116	El centro Noria	4	site	1
117	El derrame	4	wide area	1
118	El diamante	4	wide area	1
119	El mogote flor	4	wide area	1
120	Estados Unidos	4	Population center	2
121	La noria	4	site	1
122	Las tetas de juana	4	wide area	2
123	Localidades	4	Population center	2
124	Loreto Zac	4	Population center	1
125	Los campamentos	4	wide area	2
126	Los pozos	4	wide area	1
127	Mirasoles	4	wide area	1
128	Mogotes	4	wide area	3
129	Mohovano	4	wide area	3
130	Monterrey	4	Population center	1

240	Noria el uno	1	site	2
241	Noria Sta Maria	1	site	1
242	Ojo de agua san andres y la cabellera	1	site	1
243	ojo de agua la cabellera	1	site	1
244	Pajonal	1	wide area	1
245	Phoenix, AZ	1	Population center	1
246	Piedras bolas	1	wide area	1
247	Potrero 1 Soledad	1	wide area	1
248	Potrero 2 Soledad	1	wide area	1
249	Potrero 1 Alamos	1	wide area	1
250	Potrero 2 Alamos	1	wide area	1
251	Potrero 3 alamos	1	wide area	1
252	Potrero los rodriguez	1	wide area	1
253	Potrero tiroteo	1	wide area	1
254	Presón del general	1	wide area	1
255	Presón mala noche	1	wide area	3
256	Rancho el kilo	1	wide area	1
257	Rio Bravo	1	wide area	1
258	Sierra de Jimulco	1	wide area	1
259	Sierra el sarnoso	1	wide area	1
260	Sierras	1	wide area	1
261	Simulaciones	1	wide area	1
262	El Tanque Mohovano	1	site	1
263	Terreno nacional	1	wide area	1
264	Uruza	1	wide area	2
265	Vias del tren	1	wide area	1
266	Villa Ocampo	1	Population center	1
267	Zona de tortuga	1	wide area	1

Table 2.4S Social-ecological units generated considering the OPSE extent depicted in Figure 8a.

SEU	Geomorphology	Hydrology Basin	Sub-basin	Land use and vegetation	land use and vegetation nomenclature	Area (km^2)
1	Planicies subhorizontales (Dv=2.5)	A. LA INDIA - L. PALOMAS	L. Palomas	Agricultura de riego	HA RA RAS RP RSP	733.786182
2	Planicies subhorizontales (Dv=2.5)	A. LA INDIA - L. PALOMAS	L. Palomas	Cuerpos de agua	H2O	1547.836849
3	Planicies subhorizontales (Dv=2.5)	A. LA INDIA - L. PALOMAS	L. Palomas	Sin vegetacion aparente	ADV DV	1835.553992
4	Planicies subhorizontales (Dv=2.5)	A. LA INDIA - L. PALOMAS	L. Palomas	Matorral desértico	MC MDM MDR MSM vsa	13134.2743
5	Planicies subhorizontales (Dv=2.5)	A. LA INDIA - L. PALOMAS	L. Palomas	Pastizal	PH PI PN vsa	7276.625383
6	Planicies subhorizontales (Dv=2.5)	A. LA INDIA - L. PALOMAS	L. Palomas	Veg de desiertos arenosos	VDA vsaVDA VG	3782.191216
7	Planicies subhorizontales (Dv=2.5)	A. LA INDIA - L. PALOMAS	L. Palomas	Veg Halofila gipsofila	VG HX vsa	7434.097008
8	Planicies onduladas (2.6<Dv<15)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Agricultura de riego	HA RA RAS RP RSP	23624.3529
9	Planicies onduladas (2.6<Dv<15)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Agricultura de temporal	TA TP TS	3644.985447
10	Planicies onduladas (2.6<Dv<15)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Cuerpos de agua	H2O	36.815186
11	Planicies onduladas (2.6<Dv<15)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Sin vegetacion aparente	ADV DV	17.866383
12	Planicies onduladas (2.6<Dv<15)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Mezquital	MK MKX vsa	808.278063
13	Planicies onduladas (2.6<Dv<15)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Matorral desértico	MC MDM MDR MSM vsa	24742.56512
14	Planicies onduladas (2.6<Dv<15)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Pastizal	PH PI PN vsa	57598.22328
15	Planicies onduladas (2.6<Dv<15)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Urbano construido	AH	107.507721
16	Planicies onduladas (2.6<Dv<15)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Veg Halofila gipsofila	VG HX vsa	6432.023702
17	Planicies onduladas (2.6<Dv<15)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Agricultura de riego	HA RA RAS RP RSP	3598.606843
18	Planicies onduladas (2.6<Dv<15)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Agricultura de temporal	TA TP TS	9494.905893

19	Planicies onduladas (2.6<Dv<15)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Cuerpos de agua	H2O	305.038674
20	Planicies onduladas (2.6<Dv<15)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Sin vegetacion aparente	ADV DV	2455.015206
21	Planicies onduladas (2.6<Dv<15)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Mezquital	MK MKX vsa	1.340597
22	Planicies onduladas (2.6<Dv<15)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Matorral desértico	MC MDM MDR MSM vsa	45699.63802
23	Planicies onduladas (2.6<Dv<15)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Pastizal	PH PI PN vsa	36819.14123
24	Planicies onduladas (2.6<Dv<15)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Veg Halofila gipsofila	VG HX vsa	35868.04858
25	Planicies onduladas (2.6<Dv<15)	L. DEL REY	L. del Rey	Cuerpos de agua	H2O	34.020994
26	Planicies onduladas (2.6<Dv<15)	L. DEL REY	L. del Rey	Sin vegetacion aparente	ADV DV	819.149158
27	Planicies onduladas (2.6<Dv<15)	L. DEL REY	L. del Rey	Matorral desértico	MC MDM MDR MSM vsa	23614.27588
28	Planicies onduladas (2.6<Dv<15)	L. DEL REY	L. del Rey	Pastizal	PH PI PN vsa	11227.80565
29	Planicies onduladas (2.6<Dv<15)	L. DEL REY	L. del Rey	Veg de desiertos arenosos	VDA vsaVDA VG	49043.22982
30	Planicies onduladas (2.6<Dv<15)	L. DEL REY	L. del Rey	Veg Halofila gipsofila	VG HX vsa	6459.50475
31	Planicies onduladas (2.6<Dv<15)	A. LA INDIA - L. PALOMAS	L. Palomas	Agricultura de riego	HA RA RAS RP RSP	6347.348256
32	Planicies onduladas (2.6<Dv<15)	A. LA INDIA - L. PALOMAS	L. Palomas	Cuerpos de agua	H2O	141.378167
33	Planicies onduladas (2.6<Dv<15)	A. LA INDIA - L. PALOMAS	L. Palomas	Sin vegetacion aparente	ADV DV	530.480912
34	Planicies onduladas (2.6<Dv<15)	A. LA INDIA - L. PALOMAS	L. Palomas	Matorral desértico	MC MDM MDR MSM vsa	35068.23397
35	Planicies onduladas (2.6<Dv<15)	A. LA INDIA - L. PALOMAS	L. Palomas	Pastizal	PH PI PN vsa	13671.69874
36	Planicies onduladas (2.6<Dv<15)	A. LA INDIA - L. PALOMAS	L. Palomas	Veg de desiertos arenosos	VDA vsaVDA VG	11527.52381
37	Planicies onduladas (2.6<Dv<15)	A. LA INDIA - L. PALOMAS	L. Palomas	Veg Halofila gipsofila	VG HX vsa	26761.36742
38	Planicies onduladas (2.6<Dv<15)	R. NAZAS - TORREON	A. La Cadena	Agricultura de riego	HA RA RAS RP RSP	13974.27786
39	Planicies onduladas (2.6<Dv<15)	R. NAZAS - TORREON	A. La Cadena	Agricultura de temporal	TA TP TS	264.001347

40	Planicies onduladas (2.6<Dv<15)	R. NAZAS - TORREON	A. La Cadena	Cuerpos de agua	H2O	133.423122
41	Planicies onduladas (2.6<Dv<15)	R. NAZAS - TORREON	A. La Cadena	Mezquital	MK MKX vsa	239.516555
42	Planicies onduladas (2.6<Dv<15)	R. NAZAS - TORREON	A. La Cadena	Matorral desértico	MC MDM MDR MSM vsa	23899.86235
43	Planicies onduladas (2.6<Dv<15)	R. NAZAS - TORREON	A. La Cadena	Pastizal	PH PI PN vsa	8140.328013
44	Planicies onduladas (2.6<Dv<15)	R. NAZAS - TORREON	A. La Cadena	Veg Halofila gipsofila	VG HX vsa	11992.30999
45	Planicies acolinadas (16<Dv<40)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Agricultura de riego	HA RA RAS RP RSP	2630.113063
46	Planicies acolinadas (16<Dv<40)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Agricultura de temporal	TA TP TS	538.074115
47	Planicies acolinadas (16<Dv<40)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Cuerpos de agua	H2O	43.362158
48	Planicies acolinadas (16<Dv<40)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Mezquital	MK MKX vsa	30.606204
49	Planicies acolinadas (16<Dv<40)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Matorral desértico	MC MDM MDR MSM vsa	21294.695
50	Planicies acolinadas (16<Dv<40)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Pastizal	PH PI PN vsa	12743.88267
51	Planicies acolinadas (16<Dv<40)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Urbano construido	AH	5.75429
52	Planicies acolinadas (16<Dv<40)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Veg Halofila gipsofila	VG HX vsa	216.397719
53	Planicies acolinadas (16<Dv<40)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Agricultura de riego	HA RA RAS RP RSP	41.902154
54	Planicies acolinadas (16<Dv<40)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Agricultura de temporal	TA TP TS	994.449827
55	Planicies acolinadas (16<Dv<40)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Cuerpos de agua	H2O	158.087152
56	Planicies acolinadas (16<Dv<40)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Mezquital	MK MKX vsa	0.647609
57	Planicies acolinadas (16<Dv<40)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Matorral desértico	MC MDM MDR MSM vsa	44109.01329
58	Planicies acolinadas (16<Dv<40)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Pastizal	PH PI PN vsa	4453.803193
59	Planicies acolinadas (16<Dv<40)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Urbano construido	AH	32.418816
60	Planicies acolinadas (16<Dv<40)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Veg Halofila gipsofila	VG HX vsa	7957.450118

61	Planicies acolinadas (16<Dv<40)	L. DEL REY	L. del Rey	Agricultura de riego	HA RA RAS RP RSP	48.084745
62	Planicies acolinadas (16<Dv<40)	L. DEL REY	L. del Rey	Agricultura de temporal	TA TP TS	82.508987
63	Planicies acolinadas (16<Dv<40)	L. DEL REY	L. del Rey	Cuerpos de agua	H2O	744.684938
64	Planicies acolinadas (16<Dv<40)	L. DEL REY	L. del Rey	Sin vegetacion aparente	ADV DV	5714.177537
65	Planicies acolinadas (16<Dv<40)	L. DEL REY	L. del Rey	Matorral desértico	MC MDM MDR MSM vsa	76971.16755
66	Planicies acolinadas (16<Dv<40)	L. DEL REY	L. del Rey	Pastizal	PH PI PN vsa	4970.904617
67	Planicies acolinadas (16<Dv<40)	L. DEL REY	L. del Rey	Urbano construido	AH	335.048186
68	Planicies acolinadas (16<Dv<40)	L. DEL REY	L. del Rey	Veg de desiertos arenosos	VDA vsaVDA VG	24222.65498
69	Planicies acolinadas (16<Dv<40)	L. DEL REY	L. del Rey	Veg Halofila gipsofila	VG HX vsa	13336.1822
70	Planicies acolinadas (16<Dv<40)	A. LA INDIA - L. PALOMAS	L. Palomas	Agricultura de riego	HA RA RAS RP RSP	1044.652645
71	Planicies acolinadas (16<Dv<40)	A. LA INDIA - L. PALOMAS	L. Palomas	Agricultura de temporal	TA TP TS	132.144736
72	Planicies acolinadas (16<Dv<40)	A. LA INDIA - L. PALOMAS	L. Palomas	Cuerpos de agua	H2O	112.649117
73	Planicies acolinadas (16<Dv<40)	A. LA INDIA - L. PALOMAS	L. Palomas	Mezquital	MK MKX vsa	112.068914
74	Planicies acolinadas (16<Dv<40)	A. LA INDIA - L. PALOMAS	L. Palomas	Matorral desértico	MC MDM MDR MSM vsa	70544.98468
75	Planicies acolinadas (16<Dv<40)	A. LA INDIA - L. PALOMAS	L. Palomas	Pastizal	PH PI PN vsa	6779.318362
76	Planicies acolinadas (16<Dv<40)	A. LA INDIA - L. PALOMAS	L. Palomas	Urbano construido	AH	61.421536
77	Planicies acolinadas (16<Dv<40)	A. LA INDIA - L. PALOMAS	L. Palomas	Veg de desiertos arenosos	VDA vsaVDA VG	2369.58059
78	Planicies acolinadas (16<Dv<40)	A. LA INDIA - L. PALOMAS	L. Palomas	Veg Halofila gipsofila	VG HX vsa	6103.690913
79	Planicies acolinadas (16<Dv<40)	R. NAZAS - TORREON	A. La Cadena	Agricultura de riego	HA RA RAS RP RSP	158.384394
80	Planicies acolinadas (16<Dv<40)	R. NAZAS - TORREON	A. La Cadena	Agricultura de temporal	TA TP TS	2.306127
81	Planicies acolinadas (16<Dv<40)	R. NAZAS - TORREON	A. La Cadena	Matorral desértico	MC MDM MDR MSM vsa	2850.516182

82	Planicies acolinadas (16<Dv<40)	R. NAZAS - TORREON	A. La Cadena	Pastizal	PH PI PN vsa	551.212302
83	Planicies acolinadas (16<Dv<40)	R. NAZAS - TORREON	A. La Cadena	Veg Halofila gipsofila	VG HX vsa	366.418218
84	Lomeríos (41<Dv<100)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Agricultura de riego	HA RA RAS RP RSP	330.24026
85	Lomeríos (41<Dv<100)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Agricultura de temporal	TA TP TS	27.782872
86	Lomeríos (41<Dv<100)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Cuerpos de agua	H2O	0.022213
87	Lomeríos (41<Dv<100)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Matorral desértico	MC MDM MDR MSM vsa	18366.86244
88	Lomeríos (41<Dv<100)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Pastizal	PH PI PN vsa	1506.729458
89	Lomeríos (41<Dv<100)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Agricultura de temporal	TA TP TS	403.749006
90	Lomeríos (41<Dv<100)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Cuerpos de agua	H2O	9.755487
91	Lomeríos (41<Dv<100)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Matorral desértico	MC MDM MDR MSM vsa	35304.45809
92	Lomeríos (41<Dv<100)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Pastizal	PH PI PN vsa	890.427223
93	Lomeríos (41<Dv<100)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Veg Halofila gipsofila	VG HX vsa	2436.032054
94	Lomeríos (41<Dv<100)	L. DEL REY	L. del Rey	Cuerpos de agua	H2O	30.372389
95	Lomeríos (41<Dv<100)	L. DEL REY	L. del Rey	Matorral desértico	MC MDM MDR MSM vsa	58286.67965
96	Lomeríos (41<Dv<100)	L. DEL REY	L. del Rey	Pastizal	PH PI PN vsa	919.21007
97	Lomeríos (41<Dv<100)	L. DEL REY	L. del Rey	Urbano construido	AH	18.89882
98	Lomeríos (41<Dv<100)	L. DEL REY	L. del Rey	Veg Halofila gipsofila	VG HX vsa	977.530116
99	Lomeríos (41<Dv<100)	A. LA INDIA - L. PALOMAS	L. Palomas	Agricultura de temporal	TA TP TS	13.855129
100	Lomeríos (41<Dv<100)	A. LA INDIA - L. PALOMAS	L. Palomas	Mezquital	MK MKX vsa	92.139443
101	Lomeríos (41<Dv<100)	A. LA INDIA - L. PALOMAS	L. Palomas	Matorral desértico	MC MDM MDR MSM vsa	32160.66718
102	Lomeríos (41<Dv<100)	A. LA INDIA - L. PALOMAS	L. Palomas	Pastizal	PH PI PN vsa	1351.803709
103	Lomeríos (41<Dv<100)	A. LA INDIA - L. PALOMAS	L. Palomas	Veg Halofila gipsofila	VG HX vsa	238.781958
104	Montañas (Dv=101)	A. LA INDIA - L. PALOMAS	A. La India - A. Cerro Gordo	Matorral desértico	MC MDM MDR MSM vsa	3113.031514

105	Montañas (Dv=101)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Agricultura de temporal	TA TP TS	76.765281
106	Montañas (Dv=101)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Matorral desértico	MC MDM MDR MSM vsa	39817.18286
107	Montañas (Dv=101)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Pastizal	PH PI PN vsa	26.726138
108	Montañas (Dv=101)	R. NAZAS - AGUANAVAL	R. Nazas - C. Santa Rosa	Veg Halofila gipsofila	VG HX vsa	336.323399
109	Montañas (Dv=101)	L. DEL REY	L. del Rey	Cuerpos de agua	H2O	1.78742
110	Montañas (Dv=101)	L. DEL REY	L. del Rey	Matorral desértico	MC MDM MDR MSM vsa	9494.214127
111	Montañas (Dv=101)	A. LA INDIA - L. PALOMAS	L. Palomas	Matorral desértico	MC MDM MDR MSM vsa	6111.273276
112	Montañas (Dv=101)	A. LA INDIA - L. PALOMAS	L. Palomas	Pastizal	PH PI PN vsa	13.901194
113	Montañas (Dv=101)	A. LA INDIA - L. PALOMAS	L. Palomas	Veg Halofila gipsofila	VG HX vsa	0.988834

Chapter 3

3.1 Validation of precipitation data by statistical homogeneity tests.

The hypotheses posed for the three statistical homogeneity tests were as follows: the null hypothesis (Ho): the data are homogeneously distributed vs the alternative hypothesis (Ha): the data are not homogeneously distributed (Table A1). The level significance (α) 0.05 was used. In category one, series whose null hypothesis tests were rejected in one of the three tests were considered reliable; in category two, series that presented two null hypotheses, the information was classified as moderately reliable and in category three, series in which three null hypotheses were rejected, the information was considered unreliable. The values in bold type describe that Ho was rejected.

Table 3.1S Statistical homogeneity tests for rain gauge stations of the study area (p-value, α = 0.05). The bold values indicate that Ho was rejected.

Code	Name	Pettitt	Prueba SNHT	Buishand	Classification
2001	Agua Caliente	0.388	**0.026**	0.143	Accepted
5026	Coyote	0.518	0.064	0.087	Accepted
5036	San Pedro	**0.030**	**0.032**	0.254	Rejected
5039	Sierra Mojada	0.097	0.1827	0.0975	Accepted
10045	Mapimi	0.722	0.267	0.339	Accepted
10085	Tlahualilo	0.454	0.100	0.449	Accepted
10108	Cd Lerdo	0.2632	0.1311	0.172	Accepted
10128	Villa Hidalgo	0.066	**0.046**	**0.006**	Rejected
5136	Las Hormigas	0.1144	0.1785	0.0528	Accepted
5176	Jame	0.121	**0.008**	**0.015**	Rejected
19020	El Potosi	0.3062	0.3095	0.1707	Accepted
19032	La Carbonera	**0.011**	**0.015**	**0.015**	Rejected
19050	San Jose de Raíces	0.840	0.144	**0.019**	Accepted
19059	Santa Rosa	0.310	0.095	0.129	Accepted
19067	El Rucio	**0.012**	**0.015**	**0.001**	Rejected
19079	El Refugio De Los Ibarra	**<0.0001**	**<0.0001**	**<0.0001**	Rejected
19115	El Cuije	0.221	**0.038**	0.059	Accepted
19135	San Francisco de Berlanga	**0.000**	**0.030**	**0.003**	Rejected

19137	San Jorge	**<0.0001**	**0.013**	**<0.0001**	Rejected
19138	Santa Ana	**0.039**	0.069	0.059	Accepted
19160	San Antonio de Texas	**0.007**	**0.010**	**0.007**	Rejected
19182	San Roberto	0.963	0.554	0.195	Accepted
32078	San Tiburcio	0.466	0.367	0.100	Accepted