Evaluación de sostenibilidad de sistemas socioecológicos tradicionales en regiones áridas mediante modelos dinámicos: El oasis de Los Comondú

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The oasis of Comondú

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HACE CONSTAR

Que da su conformidad a la lectura de la tesis doctoral presentada por Alicia Tenza Peral, titulada "Evaluación de sostenibilidad de sistemas socioecológicos tradicionales en regiones áridas mediante modelos dinámicos: el oasis de Los Comondú", que se ha desarrollado dentro del Programa de Doctorado en Análisis y Gestión Ambiental de este Departamento, bajo la dirección de Dr. Andrés Giménez Casalduero y Dra. Julia Martínez Fernández.

Lo que firmo en Elche, a instancias oportunas, a diecisiete de julio de dos mil diecisiete.

Dr. Ignacio Gómez Lucas
Director del Departamento de Agroquímica y Medio Ambiente

Índice

Resumen

Desde las últimas décadas del siglo XX nuestra concepción y percepción del mundo ha cambiado estrepitosamente. Lejos queda la visión de un mundo parcelado entre lo natural y lo antrópico, de recursos inagotables, y de causas y efectos limitados a nuestro entorno más cercano. Despertamos en un mundo profundamente interconectado, con intercambios de materiales, energía, información y personas a ritmo vertiginoso. Un mundo donde el crecimiento y el consumismo exacerbado de unos, es mantenido por el expolio de los recursos naturales y la pobreza de otros. Los desafíos que enfrentamos hacen necesarios nuevos enfoques más integradores, multidisciplinares, que tengan en cuenta la complejidad de los sistemas, la pluralidad del conocimiento, y la participación activa de la ciudadanía. Ante esta necesidad ha surgido en el siglo XXI la ciencia de la sostenibilidad, nuevo paradigma que aborda problemas reales desde la perspectiva de los sistemas complejos, y se orienta hacia la resolución de los mismos. Los sistemas socioecológicos se convierten en la unidad fundamental de estudio de este paradigma. El concepto de sistema socioecológico comprende la base de recursos naturales de los sistemas, las instituciones creadas para aprovechar estos recursos, y la población humana organizada en torno a estas instituciones.

La insostenibilidad del sistema socioecológico global hace acuciante buscar mecanismos y modelos de uso y gestión de recursos naturales alternativos, capaces de perdurar en el tiempo y ser resilientes. Los sistemas socioecológicos tradicionales son ejemplos de sistemas que han perdurado en el tiempo, con instituciones locales para el uso y distribución de los recursos naturales bien adaptadas a la variación natural de estos recursos y a perturbaciones frecuentes en su historia. Sin embargo, estos sistemas tradicionales relativamente aislados del sistema global son cada vez más influenciados por las dinámicas globales, tanto derivadas del proceso de globalización, como de cambio climático. Los estudios caso-específicos de este tipo de sistemas son clave para entender su funcionamiento, y sobre todo, para atender las problemáticas específicas que los amenazan. Desde la perspectiva de la ciencia de la sostenibilidad, la gestión de estos sistemas socioecológicos se considera un factor crucial para impulsar la sostenibilidad global. A pesar de la importancia de estos sistemas, la mayor parte de los estudios existentes sobre sistemas socioecológicos permanecen en el plano teórico y conceptual, lo que dificulta su aplicación práctica.

La presente tesis es el resultado de una investigación a largo plazo sobre un sistema socioecológico tradicional de pequeña escala, el oasis de Los Comondú en Baja California Sur, México, que entró en declive a mitad del

del siglo pasado, afectado por los procesos derivados del cambio global. El objetivo general de la presente tesis es analizar las causas estructurales de este declive, y en base a este conocimiento, evaluar medidas de gestión que puedan ayudar a frenar y revertir el declive de este sistema y contribuir a su gestión sostenible. Para ello, bajo el enfoque teórico y metodológico de la Dinámica de Sistemas hemos desarrollado un modelo de gestión. Esta metodología es idónea para el objetivo propuesto, dado que permite estudiar la evolución de los sistemas a largo plazo, tener en cuenta las interacciones y sinergias entre factores, e integrar factores sociales, económicos y ambientales. El proceso de construcción de este tipo de modelos es dividido en tres grandes etapas: la conceptualización del sistema de estudio, la elaboración y validación del modelo cuantitativo, y la exploración de escenarios de gestión. Tanto los objetivos específicos de esta tesis, como su estructura, están ligados a este proceso. Siendo los objetivos específicos: i) conceptualizar el sistema de estudio, y construir un modelo cualitativo como hipótesis estructural explicativa del comportamiento histórico observado; ii) construir y validar el modelo cuantitativo que simule el comportamiento histórico del sistema, y analizar los efectos de las variables externas sobre la dinámica endógena del sistema; y iii) identificar los puntos más sensibles del sistema que podrían ser intervenidos a través de medidas de gestión, y evaluar el efecto de estas potenciales intervenciones en la dinámica del sistema. La tesis se compone de tres capítulos que abordan estos objetivos específicos. Estos capítulos son artículos publicados y/o enviados a revistas científicas de impacto.

En el Capítulo 1 se ha descrito el proceso de conceptualización del sistema de estudio y su problemática. A partir de técnicas de investigación social (entrevistas en profundidad y observación participante), la participación de un panel interdisciplinar de expertos, la revisión bibliográfica y estadísticas oficiales, se construyó un modelo cualitativo que ha permitido explicar el comportamiento problemático observado (i.e. proceso de despoblamiento y declive del sistema). Este modelo conceptual constituye nuestra hipótesis estructural del sistema, sobre la cual se desarrollan los siguientes capítulos. Además de esta hipótesis estructural, se definen una serie de hipótesis dinámicas sobre el efecto de las variables externas (que representan cambios ambientales y socioeconómicos en la escala regional y global) sobre la dinámica endógena del sistema. Los resultados obtenidos en este primer capítulo demuestran la utilidad del enfoque de la Dinámica de Sistemas en la construcción de modelos cualitativos, ya que permiten profundizar en las relaciones causa-efecto de las dinámicas observadas de los sistemas socioecológicos, a diferencia de otros enfoques recurrentes en la literatura que permanecen con un alto nivel de abstracción. Este trabajo ha sido publicado en la revista *Ecology and Society*.

En el Capítulo 2, se ha descrito el modelo cuantitativo "SESSMO" (por el acrónimo en inglés de "Social-Ecological System Sustainability Model") y el proceso de validación formal de éste. Con el modelo validado, se han realizado una serie de simulaciones experimentales para cuantificar el peso de las variables externas en la dinámica del sistema e identificar las sinergias y trade-offs que se producen entre ellas. SESSMO simula el comportamiento observado de las principales variables del sistema (i.e. población, superficie de regadío, ranchos, ganado caprino y bovino). Las pruebas estructurales y los análisis de sensibilidad mostraron un elevado grado de confianza en la capacidad del modelo de comportarse como el sistema real, incluso fuera de las condiciones bajo las cuales fue calibrado. El ajuste estadístico entre datos observados y simulados fue bueno. Se puede considerar, por tanto, que nuestra hipótesis estructural de partida es válida. Sin embargo, las hipótesis dinámicas sobre el efecto de las condiciones externas sobre el sistema, aunque acertadas en su mayoría, difirieron en magnitud. Inicialmente pensamos que dentro de las políticas de desarrollo regional identificadas a mitad del siglo XX, el proceso de colonización y modernización agraria de Baja California Sur y la deslocalización sociopolítica de los oasis, habían tenido una gran influencia en la dinámica de declive de este sistema. Mientras que, la creación del ejido Comondú (i.e. entrega de tierras comunales) había tenido un efecto contrario, frenando el proceso de despoblamiento y aliviando la escasez de empleo local y la situación económica. No obstante, la creación del ejido Comondú también la relacionamos con un incremento de la sensibilidad y vulnerabilidad de todo el sistema a eventos climáticos extremos por haber impulsado la ganadería caprina. Los resultados evidenciaron que estos factores influyeron de la manera señalada. Sin embargo, la dinámica del sistema socioecológico estuvo más fuertemente condicionada por los factores dependientes de los procesos globales, como son el clima y los precios de mercado, que por estos cambios regionales. A pesar de ello, ni factores globales ni regionales han podido explicar por si solos el origen del decaimiento de este sistema. Parece que las condiciones endógenas iniciales en torno al empleo y a la economía del oasis tuvieron una importancia destacada en el inicio del proceso de despoblamiento. Sin embargo, es posible que algún factor no identificado en el proceso de conceptualización tenga también un papel explicativo, como podría ser la tenencia de la tierra y la distribución de la misma. Entre las principales interacciones entre los cambios regionales y globales, identificamos una relación de compensación o "trade-off" entre los factores regionales y los globales, y una relación de sinergia bastante marcada entre las variables climáticas y los precios de mercado. Esto último, parece indicar que el sistema socioecológico del oasis de Los Comondú es doblemente vulnerable tanto a los efectos del cambio climático, como a los efectos derivados del fenómeno de la globalización. Este trabajo ha sido enviado a la revista *Global Environmental Change*.

En el Capítulo 3, se utilizó el modelo SESSMO y la herramienta del análisis de sensibilidad para identificar los parámetros más sensibles del sistema que pueden actuar como potenciales puntos de palanca, provocando cambios cualitativos en la dinámica del sistema con un menor esfuerzo. Mediante la simulación de escenarios de gestión basados en la mejora de estos parámetros, se evaluó el desempeño de estas palancas en relación con su capacidad de frenar o incluso revertir el proceso de declive del sistema. Los resultados obtenidos se compararon con las medidas de gestión propuestas por los principales actores (i.e. la población local del oasis, el gobierno regional de Baja California Sur, y la academia). Estas propuestas se recogieron mediante la realización de un taller participativo en las comunidades locales del oasis de Los Comondú, la revisión de las entrevistas en profundidad que se hicieron durante el proceso de conceptualización, la revisión de los planes estratégicos del gobierno regional de Baja California Sur, y la revisión de las publicaciones del equipo interdisciplinar de expertos que colaboró en el proceso de conceptualización. Respecto a los puntos de palanca del sistema, se identificaron cinco parámetros clave del sistema, intervenibles por medidas de gestión, que podrían provocar cambios en la dinámica del sistema con un esfuerzo relativo. Estos cinco parámetros se pueden categorizar en tres grupos: i) rendimiento bovino, ii) rendimiento caprino, y iii) rendimiento agrícola. Los resultados muestran una mejora en indicadores clave relacionados con el empleo y la economía local del oasis, así como una ralentización del proceso de despoblamiento. La mejora de los rendimientos ganaderos (caprinos y bovinos) es la intervención con mayor impacto en la dinámica del sistema. Sin embargo, los mejores resultados, en relación con el objetivo de frenar o incluso revertir el despoblamiento del oasis, se obtuvieron al mejorar conjuntamente el rendimiento agrícola y el ganadero. Se ralentiza el proceso de despoblamiento y durante la última década de la simulación hay un incipiente crecimiento poblacional. Sin embargo, parece que el sistema requiere de cambios estructurales para revertir el proceso de despoblamiento y estabilizar su dinámica bajo un escenario climático y económico incierto. La población local del oasis y la academia (i.e. equipo interdisciplinar de expertos) han sido los actores cuyas medidas de gestión propuestas coinciden en mayor medida con los puntos de palanca del sistema. El gobierno regional de Baja California Sur fue el actor con las propuestas más distantes a estos puntos de palanca del sistema, pero también el más distante a las demandas de la población del oasis. Este trabajo ha sido enviado a la revista *Frontiers in Ecology and the Environment.*

La presente tesis demuestra que es posible avanzar en el estudio de los sistemas socioecológicos con aproximaciones más formales que permiten su aplicación directa, tanto para analizar los efectos de cambios ambientales y socioeconómicos en escalas superiores, como para evaluar y proponer medidas de gestión que puedan apoyar los procesos de toma de decisión. El conocimiento local, recabado por técnicas de investigación social, se convierte en una fuente complementaria a los datos oficiales recabados por medios convencionales, capaz de ayudar a vencer las dificultades de la modelación de sistemas socioecológicos a escala local. Los estudios de sistemas socioecológicos, especialmente cuando han de derivarse recomendaciones de ellos, no pueden quedarse a nivel cualitativo. Nuestros resultados evidencian la limitación de los modelos mentales en establecer la magnitud de efectos, y en identificar interacciones propias de los sistemas complejos como trade-offs y sinergias. La presente tesis constituye una de las primeras investigaciones a largo plazo sobre un sistema socioecológico tradicional que cuantitativamente analiza el proceso de declive de este tipo de sistemas a través de un modelo de simulación cuantitativo, determina el peso relativo de los efectos de los cambios ambientales y socioeconómicos en las escalas regional y global sobre este declive, e identifica y mide las interacciones entre las escalas local, regional y global.

La evaluación de medidas de gestión, incluyendo aquellas que supongan cambios estructurales, bajo escenarios futuros de cambio climático y cambio socioeconómico, se perfilan como próximos pasos de esta investigación. Se espera que tanto los resultados de esta tesis, así como los que se generen en los futuros pasos de esta investigación, sirvan de apoyo en los procesos de toma de decisión encaminados a revitalizar este sistema socioecológico tradicional, mejorar la calidad de vida de sus habitantes, y contribuir en su transición hacia la sostenibilidad.

Summary

Since the last decades of the twentieth century, our perception about the world has changed dramatically. We live in a deeply interconnected world, with rapid exchanges of materials, energy, information and people. It is a world where growth and exacerbated consumerism are maintained by the exploitation of natural resources and social inequality. The challenges we face require new, more inclusive, multidisciplinary approaches that take into account the complexity of systems, the plurality of knowledge, and the active participation of citizens. The sustainability science, a new paradigm oriented to solve specific problems from the perspective of complex systems, has emerged in the 21st century from this need. The sustainability of social-ecological systems is the main concern of the sustainability science. The concept of social-ecological systems comprises the natural resources, the institutions created to take advantage of these resources, and the human population organized around these institutions.

The unsustainability of the global social-ecological system urges to seek alternative sustainable models for the use and management of natural resources. Long-lived social-ecological systems are examples of these alternative models. They are characterized by local institutions for the use and distribution of natural resources, which are well adapted to the natural variation of these resources and to frequent disturbances in their history. However, these systems are increasingly influenced by global dynamics, both derived from the globalization process and from climate change. Case-specific studies of these types of systems are key to understand their functioning and, above all, to address the specific problems that threaten them. From the perspective of the sustainability science, the management of these social-ecological systems is considered a crucial factor to promote global sustainability. Despite the importance of these systems, most existing studies on social-ecological systems still entail a high level of abstraction, making it difficult to apply them in practice.

This thesis is the result of a long-term research about a small-scale, long-lived, social-ecological system in Baja California Sur (Mexico), which has undergone a dramatic transition from growth to decline in the past century, influenced by environmental and socio-economic changes on global and regional scales. The general objective of this thesis is to analyze the structural causes of this decline and, based on this knowledge, to evaluate management measures that can help to reverse the decline of this system and contribute to its sustainable management. For this, under the theoretical and methodological approach of the System Dynamics we have developed a

management model. This methodology is suitable for the proposed objective, since it allows studying the evolution of systems in the long term, to take into account the interactions and synergies between factors, and to integrate social, economic and environmental factors. The process of developing this type of model is divided into three main steps: the conceptualization of the system, the elaboration and validation of the quantitative model, and the exploration of management scenarios. Both the specific objectives of this thesis and its structure are linked to this process. The specific objectives are: i) to conceptualize the study system and to develop a qualitative model as a structural hypothesis capable to explain the historical behavior; ii) to build-up and validate the quantitative model that simulates the historical behavior of the system and analyze the effects of the external drivers on the system's endogenous dynamics; and (iii) to identify the most sensitive points in the system that could be addressed through management measures and evaluate the effect of these potential interventions on the system's dynamics. The thesis consists of three chapters that address these specific objectives. These chapters are articles published and / or sent to scientific impact journals.

Chapter 1 describes the conceptualization process of the system. A qualitative model that explains the observed problematic behavior (ie. depopulation process) was developed by means of social research techniques (in-depth interviews and participant observation), the participation of an interdisciplinary panel of experts, literature review and official statistics. This conceptual model constitutes our structural hypothesis of the system, on which the following chapters are developed. In addition to this structural hypothesis, a series of dynamical hypotheses about the effects of external drivers (representing environmental and socio-economic changes on regional and global scales) on the endogenous dynamics of the system were defined. The results obtained in this first chapter demonstrated the usefulness of the Systems Dynamics approach to build qualitative models that allow to deepen the cause-effect relationships of the observed dynamics of social-ecological systems, unlike other recurrent approaches in the literature that remain with a high level of abstraction. This work has been published in the journal Ecology and Society.

In Chapter 2, the quantitative model "SESSMO" (from "Social-Ecological System Sustainability Model") and the formal validation process are described. With the validated model, a series of experimental simulations were performed to quantify the relative weight of the effects of external drivers on the system's endogenous dynamics, and to identify the synergies and trade-offs that occur between them. SESSMO simulated the observed behavior of the main system's variables (i.e. population, irrigated area, ranches, goat and cattle). Structural tests and sensitivity analyses showed a high degree of confidence in the model ability to behave as the real system, even outside the conditions under which it was calibrated. The statistical fit between observed and simulated data was good. Our results agreed with most of our dynamical hypotheses, especially as regards the consequences of the external drivers, but not as to the magnitude of these effects: i) development of more technical and modern agriculture in BCS, and the socio-political relocation of the oasis (in terms of reducing public investment) promoted the depopulation of the oasis; ii) delivery of common lands through the creation of the ejido Comondú halted the depopulation process and boosted the role of livestock activity; iii) both the creation of the ejido Comondú and dependence on livestock activity increased the vulnerability (and sensitivity) of this SES to extreme weather events (droughts and hurricanes). However, our results evidenced that the general role of regional development policies was limited. The external drivers linked to global processes, especially climatic ones, had more influence on the dynamics of this system. Despite of this, and contrarily to what was expected, the effects of the external drivers (neither the regional nor the global drivers) did not explain the decline of this social-ecological system. It seems that the initial endogenous conditions around employment and the economy of the oasis had a greater importance in the beginning of the process of depopulation. However, it is possible that some unidentified factor in the conceptualization process also had an explanatory role, such as land distribution. The synergic relation between rainfall variability and variability of market prices, and the synergy that arose between hurricanes and rainfall variability warn about the vulnerability of this SES to the double climate change and globalization exposure. This work has been submitted to the journal *Global Environmental Change.*

In Chapter 3, the SESSMO model and the sensitivity analysis tool are used to identify the most sensitive parameters of the system that can act as potential leverage points, triggering qualitative changes in system's dynamics with less effort. By means of the simulation of management scenarios based on the improvement of these parameters, the performance of these leverage points was evaluated in relation to their ability to slow or even reverse the system decline process. The results obtained were compared with the management measures proposed by the stakeholders (i.e. the local population of the oasis, the Baja California Sur regional government and the academy). These proposals were collected by conducting a participatory workshop in the local communities, reviewing the in-depth interviews that were done during the conceptualization process, reviewing the strategic plans of the regional government of Baja California Sur and reviewing the publications of the interdisciplinary team of experts who collaborated in the conceptualization process. With respect to the leverage points of the system, five key parameters modifiable by management measures were identified. These parameters, whose change could improve the dynamics of the system with a relative less effort, were categorized into three main groups: i) cattle yields, ii) goat yields, and iii) agricultural yield. The results showed an improvement in employment and economy indicators, as well as a deceleration of the depopulation process. The improvement of livestock yields (goats and cattle) was the intervention with greater impact on the system's dynamics. However, the best results were obtained by jointly improving agriculture and livestock yields. The depopulation process decelerated, and the population in the last decade of simulation slightly increased. Notwithstanding in all the management scenarios, the depopulation trend remained throughout the simulation period as a whole. It seems that the system requires structural changes to reverse the depopulation process in a sustainable way. Local actors and the academia were the stakeholders whose proposals agreed largely with the identified leverage points. The regional BCS government focused on the proposals of public services and subsidies. This government was the most distant group to both the potential leverage points, and local actors' priorities. This work has been submitted to the journal *Frontiers in Ecology and the Environment*.

The present thesis demonstrates that it is possible to advance in the study of social-ecological systems with more formal approaches that allow a direct application, both to analyze the effects of environmental and socioeconomic changes at higher scales, and to evaluate and propose management measures that can support decision-making processes. Local knowledge, gathered by social research techniques, becomes a complementary source to the official data collected by conventional procedures, useful to overcome the difficulties of modeling small-scale social-ecological systems. The study of social-ecological systems, especially when recommendations are to be derived from them, cannot remain at the qualitative level, since our results show the limitation of mental models in establishing the magnitude of effects and in identifying complex interactions such as trade-offs and synergies. The present thesis is one of the first long-term studies about a small-scale, long-lived, social-ecological system that quantitatively analyzes the decline of this type of systems through a quantitative simulation model, determines the relative weight of the effects of regional and global drivers on this decline, and identifies and measures the cross-scale interactions from local to global scale.

The evaluation of management measures, including those involving structural changes, under future climatic and socio-economic scenarios, are outlined as next steps of this research. We hope that the results of this thesis, as well as those generated in future steps, will contribute to support the decision-making processes to revitalize this long-lived social-ecological system, improve the quality of life of the local population, and promote the transition towards sustainability.

INTRODUCCIÓN

*Huerta de Don Luis Toba Moreno (fotografía de Andrés Giménez Casalduero)

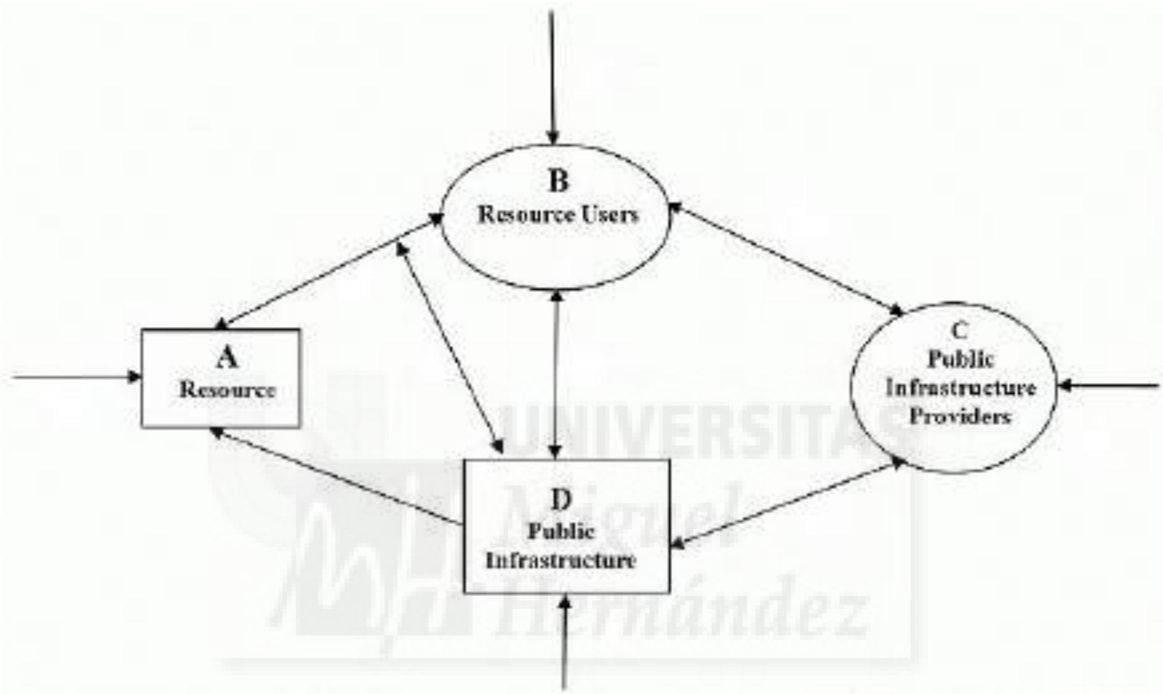
1. Introducción

1.1. Los sistemas socioecológicos

Durante siglos, el pensamiento occidental dominante que caracteriza a nuestra sociedad global, ha establecido una marcada dicotomía entre lo natural y lo antrópico. Esta separación arbitraria y artificial marcó profundamente el desarrollo del conocimiento científico y hasta nuestro propio comportamiento como sociedad, al considerar los sistemas sociales y económicos al margen de las limitaciones físicas del medio natural. A mitad del siglo XX confluyeron varios factores que favorecieron la aparición de nuevas concepciones que superan esta falsa dicotomía. Por un lado, irrumpieron problemáticas de índole global que pusieron sobre la mesa la interconexión entre las actividades humanas y el deterioro de la naturaleza a escalas globales o muy amplias. Como ejemplos paradigmáticos, cabe citar el efecto de pesticidas y su bioacumulación en los seres vivos evidenciado por la obra de Rachel Carson "La primavera silenciosa"; la aparición del agujero en la capa de ozono a consecuencia de los clorofluorocarbonos (CFC) y el incremento paulatino de la temperatura global a consecuencia del incremento de dióxido de carbono en la atmósfera. Por otro lado, emergieron nuevos enfoques más integradores y holísticos, como la teoría general de sistemas de Ludwig von Bertalanffy, la dinámica de sistemas de Jay W. Forrester y la cibernética de Norbert Weiner. De la confluencia de las crecientes problemáticas complejas y del avance en estos nuevos enfoques surge ya en el siglo XXI la ciencia de la sostenibilidad, cuyo objetivo es dar respuesta a los problemas globales, cada vez más acuciantes, que ponen en riesgo nuestra propia supervivencia. La ciencia de la sostenibilidad se inscribe en un nuevo paradigma (ciencia de los sistemas complejos) que se aleja del paradigma convencional de la ciencia positivista (Haag 2001), al proponer para la resolución de problemas reales aproximaciones inter y transdisciplinarias, la reconciliación entre las ciencias sociales y las ciencias bio-físicas, el diálogo de saberes (pluralidad del conocimiento y sus fuentes) y la participación activa de la ciudadanía. Este nuevo paradigma de la ciencia de la sostenibilidad aborda problemas reales, cuya definición permanece abierta; es dependiente del contexto; se orienta a la resolución de problemas; presta una atención profunda a la incertidumbre y considera de forma explícita la relación entre el conocimiento y el proceso de toma de decisiones y sus actores (Haag 2001).

Los sistemas socioecológicos (SSE) se erigen como las unidades fundamentales de estudio. Este concepto pretende enfatizar la interrelación del ser humano con la naturaleza, cuyos límites entre componentes sociales y ecológicos son difusos (Berkes y Folke 1998). El SSE comprende: i) la base de recursos naturales (componentes geofísicos y biológicos), que tienen sus propias dinámicas, y que proveen de servicios ecosistémicos a la población humana; ii) las instituciones creadas para aprovechar los recursos, distribuir los beneficios de su aprovechamiento, y adaptarse a la disponibilidad de los mismos; y iii) la población humana que se organiza en torno a estas instituciones y se abastece de los recursos naturales (Figura 1).

Figura 1. Esquema conceptual de la estructura de los sistemas socioecológicos. Extraído de Anderies *et al*. (2004).



Este esquema es un modelo simplificado de la estructura de los SSE, que remarca los principales componentes y sus interacciones. Pero además, los SSE además de complejos se organizan jerárquicamente a través de diferentes escalas tanto en la componente biofísica como en la institucional, las cuales interaccionan y se afectan entre sí (Berkes *et al*. 2003).

1.1.1. *Crisis del sistema socioecológico global*

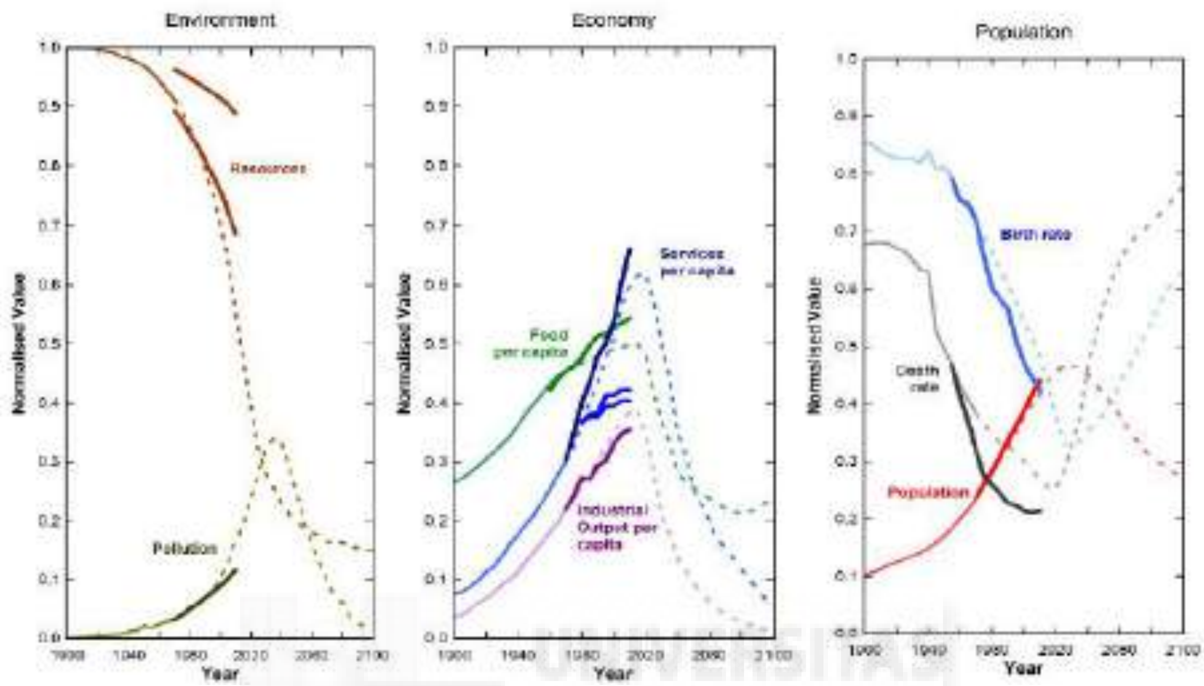
Pertenecemos a una sociedad global, la cual presenta, como una de sus metas básicas, crecer económicamente e incrementar su bienestar. No obstante, para conseguir estas metas requiere de un consumo material y energético masivo. A esta parte de la población mundial se le denomina comúnmente como el Norte Global. La demanda es tan alta que no puede ser satisfecha en el entorno inmediato. La mayor parte de los recursos necesarios para satisfacer esa demanda provienen de países y territorios cuyo desarrollo, basado en indicadores de crecimiento económico, es más bajo. A esta otra parte de la población se le conoce como el Sur Global. Nuestro sistema global se mantiene en base a la explotación masiva de recursos naturales y a una marcada desigualdad social en la relación Norte-Sur. El 20% de la población mundial más rica consume el 86% de los recursos, mientras que el 20% más pobre solo consume el 1,3% (González de Molina y Toledo 2014).

Se estima que entre 925 y 1.045 millones de personas en el mundo viven en condiciones de hambruna (FAO 2012). Dos tercios de los servicios ecosistémicos mundiales están en estado de deterioro a consecuencia de las actividades humanas (MEA 2005). Se estima que la extracción de recursos naturales se sitúa en un 35% por encima de los ritmos de renovación de los mismos (MEA 2005). La pérdida de suelos se ha estimado en torno al 20% en tierras agrícolas, 30% en bosques y 10% en pastizales (Bai *et al*. 2008). El ritmo de extinción de especies actual es superior a 100 veces el ritmo natural de extinción, por lo que algunos autores apuntan a que estamos inmersos en la "sexta gran extinción" (Ceballos *et al*. 2015). El grado de impacto de nuestras actividades sobre el Sistema Tierra es tal, que ya se ha aceptado que hemos cambiado de era geológica. Hemos dejado la estabilidad del Holoceno, para pasar al Antropoceno (Crutzen and Stoermer 2000). Los datos evidencian que estamos en una crisis social, económica y ambiental que ha sido tildada de crisis civilizatoria (Toledo 2012).

Además de éstos y otros datos que evidencian la magnitud del impacto humano sobre la biosfera, en los últimos años varios estudios y modelos muestran preocupantes tendencias de nuestro sistema global. Uno de los modelos globales más famosos fue *World 3* (Meadows *et al*. 1972), publicado en el libro "Los límites al crecimiento". Este modelo, que fue ampliamente criticado, tenía la finalidad de hacer reflexionar sobre los límites físicos del planeta y su relación con las dinámicas de crecimiento de factores como la población o el capital industrial y evaluar comparativamente los efectos de medidas de gestión basadas en la mejora tecnológica frente a los efectos de cambios estructurales. El escenario tendencial, en el cual no se realizaba ningún cambio, era el escenario más negativo de todos, bajo el cual se producía el colapso de nuestra sociedad global a largo plazo. La alarma que produjeron estos resultados se ha reavivado recientemente con la actualización de la serie de datos históricos de las principales variables del modelo. El mejor ajuste entre datos observados y simulados se produce con el escenario tendencial (Figura 2, Turner 2014).

En 2009, un equipo interdisciplinar de expertos (Rockström *et al*. 2009), propuso nueve indicadores vinculados a procesos reguladores del Sistema Tierra (ej. cambio climático, acidificación de océanos, ciclos biogeoquímicos de nitrógeno y fósforo). Se definió el valor límite de cada uno de estos

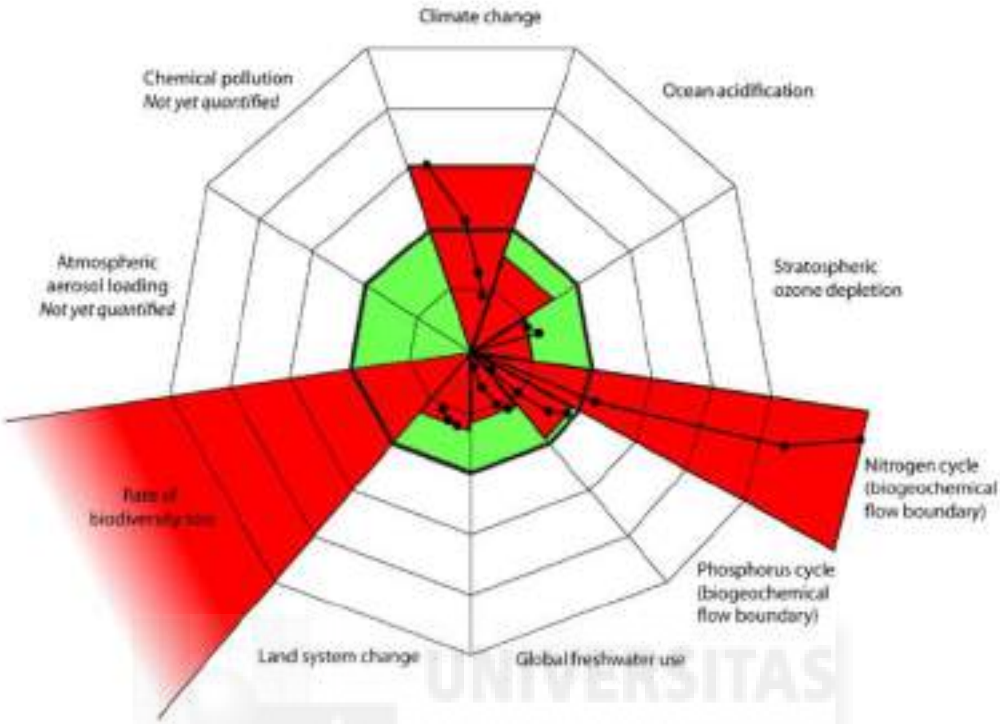
Figura 2. Datos observados actualizados de las principales variables del modelo *World 3* y su comparación con el escenario tendencial. Extraído de Turner (2014).



indicadores, entendido como el umbral por debajo del cual el sistema opera en condiciones seguras para nuestra propia supervivencia. Se calculó el estado actual de siete de ellos. Los resultados indicaron que hemos superado tres de los límites propuestos, lo cual podría actuar en cascada, facilitando la transgresión de más umbrales o incluso provocando cambios abruptos en el funcionamiento del sistema. Los tres límites superados están relacionados con la concentración de dióxido de carbono en la atmósfera, la pérdida de biodiversidad, y los cambios en el ciclo global del nitrógeno (Figura 3).

Otro modelo con interesantes implicaciones respecto al comportamiento de nuestro sistema socioecológico global es HANDY (Motesharrei *et al*. 2014). Este modelo está basado en el modelo de Brander y Taylor (1998) para la dinámica poblacional de La Isla de Pascua, el cual tenía una estructura básica "depredador-presa", en el que la población humana se comportaba como depredador y los recursos naturales como presa. En este nuevo modelo se añade una característica propia de las sociedades, que es la división por clases (élite y trabajadores). Tras varios experimentos de simulación se comprueba que hay dos posibilidades de colapso, una por el agotamiento de la base de recursos naturales, y otra por el agotamiento de la mano de obra necesaria para mantener el sistema. Los factores implicados en estos colapsos son la tasa de explotación de los recursos naturales y la desigualdad social. Al igual que ha sucedido en muchas civilizaciones avanzadas del pasado, nuestro SSE global puede colapsar. La reducción de la tasa de consumo de recursos

Figura 3. Evaluación del estado de los límites planetarios de procesos reguladores clave en el funcionamiento del Sistema Tierra. Extraído de Rockström *et al*. (2009).



naturales y la reducción de la desigualdad social se señalan como acciones que pueden evitar este colapso.

De lo expuesto hasta aquí se deduce que la dinámica actual de nuestro SSE global es insostenible. Las proyecciones futuras estiman que para 2050 seremos más de 9.000 millones de personas, lo cual incrementará la presión sobre la base de recursos naturales y posiblemente agudice la desigualdad social. La búsqueda de modelos de vida y de uso de los recursos naturales sostenibles se convierte ahora en una prioridad para modificar nuestra trayectoria. Tras los resultados de la Evaluación de Ecosistemas del Milenio (MEA2005), desde Naciones Unidas se lanzaron en 2011 y 2013 los programas de investigación a escala global: "Programme on Ecosystem Change" y "Future Earth, research for global sustainability", específicamente diseñados para llevar a cabo estudios caso-específicos (a escala regional y local) y de larga duración sobre SSE con el fin de mejorar las condiciones locales hacia dinámicas sostenibles (Carpenter *et al*. 2012, Balvanera *et al*. 2017). Se considera que el éxito en el estudio de las dinámicas complejas de estos sistemas, la comprensión de su interacción con los cambios que se producen a otras escalas, y la mejora en nuestra capacidad de acción pueden actuar como palancas de cambio, impulsando respuestas efectivas. La gestión de estos SSE de escalas más pequeñas se considera un factor crucial para impulsar la sostenibilidad global.

1.1.2. *Los sistemas socioecológicos tradicionales: oasis dentro de un mundo globalizado*

La compleja y estrecha relación que algunas sociedades han establecido con el medio natural se refleja en los múltiples paisajes culturales que a día de hoy persisten como enclaves de alto valor ecológico, histórico, estético y cultural. Ejemplos de estos paisajes son los regadíos tradicionales del levante español, los sistemas agroforestales de Latinoamérica, o los sistemas agrosilvopastoriles como las dehesas, entre otros muchos. La persistencia de estos paisajes tradicionales es una prueba de cómo el ser humano es capaz de diseñar sistemas de aprovechamiento de los recursos naturales sostenibles durante siglos, o incluso milenios (Egea-Fernández y Egea-Sánchez, 2010). En muchos casos se trata de sistemas con un alto grado de autosuficiencia (de bajos o nulos requerimientos de insumos), con un importante acervo genético de variedades locales, mejor adaptadas a las condiciones específicas de cada región y con un incalculable patrimonio inmaterial, representado por el conocimiento transmitido y enriquecido generación tras generación (ej. conocimiento local y/o conocimiento ecológico local, Gadgil *et al*. 1993, Toledo y Barrera-Bassols, 2008). No obstante, y a pesar de lo mencionado, hay que recalcar que estos sistemas no son perfectos (Altieri 1999) y no necesariamente son ejemplos de desarrollo sostenible, puesto que la sostenibilidad de un sistema no solo depende del componente medioambiental. Un claro ejemplo de esto fueron las dehesas tradicionales de Extremadura y Andalucía. Estos sistemas agrosilvopastoriles están caracterizados por una elevada complementariedad entre sus actividades y un estrecho acoplamiento de los aprovechamientos productivos con la dinámica ecosistémica, pero las fuertes desigualdades sociales, aunadas al proceso de desvalorización del campo español, motivaron una fuerte crisis que los llevó al declive (Acosta-Naranjo 2002).

Los SSE tradicionales son sistemas que han quedado relativamente al margen de las dinámicas de nuestro SSE global. En muchos casos, son sistemas con instituciones locales bien adaptadas a la variación natural de los recursos naturales y a perturbaciones frecuentes en su historia (ej. la ganadería itinerante o los regadíos tradicionales que planifican los movimientos y las tandas de riego, respectivamente, en función de la disponibilidad de agua). Si bien estos sistemas están fuertemente adaptados a determinados rangos de variación de distintos factores y a perturbaciones frecuentes dentro de tales rangos, son a la vez altamente vulnerables a cambios en dichos rangos de variación natural, así como a la aparición de nuevas perturbaciones (Carlson y Doyle 2002, Janssen *et al*. 2007). Aun relativamente aislados, estos sistemas están ahora amenazados por los efectos del cambio global. Están doblemente expuestos a las presiones socioeconómicas y cambios culturales derivados del fenómeno de globalización (Young *et al.*, 2006) y a los cambios en los regímenes de precipitación y temperatura, con posible agudización de fenómenos meteorológicos extremos a consecuencia del cambio climático (O´Brien y Leichenko 2000).

La importancia del estudio de estos SSE tradicionales conecta directamente con la búsqueda antes mencionada de modelos de vida y de uso sostenible de los recursos naturales. Aun siendo sistemas imperfectos, su relativo aislamiento de las dinámicas globales los convierte en lugares clave donde poder activar procesos de transición efectivos hacia estructuras y dinámicas realmente sostenibles y resilientes frente a la incertidumbre climática y socioeconómica futura. A día de hoy, podemos afirmar que estos sistemas contribuyen a la diversidad institucional (Janssen *et al*. 2007), a la seguridad alimentaria ya que estos sistemas campesinos de pequeña escala producen el 80% de los alimentos a escala mundial (FAO 2014), y a la conservación de la biodiversidad (Perfecto *et al*. 2009).

1.2. El rol de las técnicas de investigación social y los procesos participativos en el estudio de los sistemas socioecológicos

Las técnicas de investigación social y los procesos participativos son factores clave para el estudio de SSE, especialmente cuando se tiene como objetivo contribuir en la transición de estos sistemas hacia la sostenibilidad.

Las técnicas de investigación social (ej. las entrevistas en profundidad, la encuesta y la observación participante), metodologías utilizadas comúnmente dentro de las ciencias sociales, son esenciales para acceder al conocimiento ecológico local de los SSE (Gadgil *et al*. 1993, Becker and Ghimire 2003, Lunas-Reyes y Andersen 2003, Tengö y Belfrage 2004). Este conocimiento, además de ser de gran ayuda para entender a nivel cualitativo la dinámica general de los SSE, y las estrategias locales de adaptación a cambios y perturbaciones (Forrester 1992, Lunas-Reyes y Andersen 2003, Tengö y Belfrage 2004), es también en muchos casos, una fuente de información (cuantitativa y semi-cuantitativa) de calidad que complementa a las técnicas más convencionales en la investigación científica (Huntington 2000, Anadón *et al*. 2009, Pérez *et al*. 2012, Parry and Peres 2015). Las técnicas de investigación social son también fundamentales para sumergirse en la realidad bajo estudio, conocer las aspiraciones y conflictos de las comunidades locales e iniciar una relación de confianza mutua con los actores locales.

El acercamiento y la buena comunicación entre los investigadores y las comunidades locales, la transparencia y el establecimiento de una buena relación de confianza, se han señalado como factores decisivos para el éxito de procesos participativos orientados a la toma de decisiones en los SSE (Palomo *et al*. 2011, Hanspach *et al*. 2014, Balvanera *et al*. 2017). En tales procesos participativos se identifican las necesidades y problemáticas locales, se busca el consenso sobre alternativas y soluciones, y se toman las decisiones sobre cuestiones que afectan directamente a las comunidades locales. La participación activa de las comunidades locales en este proceso es condición indispensable para el apropiamiento de los resultados y para que las estrategias planteadas sean ejecutadas y monitoreadas de manera efectiva (Reed 2008).

Tanto el acercamiento a las comunidades locales como el desarrollo de procesos participativos requieren de tiempo. Es por ello que el planteamiento actual para el estudio de SSE se basa en estudios a largo plazo (Carpenter *et al*. 2012, Balvanera *et al*. 2017). Esto es un desafío dentro de los esquemas convencionales científicos, ya que buena parte de la financiación y de la valoración del trabajo científico depende casi exclusivamente de la publicación científica en revistas de alto impacto, lo cual puede entrar en conflicto con la dedicación de tiempo suficiente al proceso de inmersión que implica, además de las aproximaciones convencionales la generación de dinámicas participativas, la retroalimentación entre las comunidades locales y los científicos, así como la comunicación en un lenguaje no científico (Balvanera *et al*. 2017).

1.3. La Dinámica de Sistemas y los modelos de gestión como enfoque metodológico

La Dinámica de Sistemas es un enfoque metodológico que, desde un punto de vista holístico, pretende analizar y dar respuesta a problemas del mundo real. Fue desarrollado por Jay W. Forrester en la década de 1950. Inicialmente aplicado a problemas industriales (Forrester 1958, 1961), ha extendido enormemente su aplicación en las últimas décadas hacia diversos campos como la gestión del agua (Martínez-Fernández y Esteve-Selma 2004, Xiao-Qing *et al*. 2012, Sanga and Mungatana 2016), el análisis de los cambios de uso de suelo (Dale *et al*. 1993, Baur and Rinder 2015, Vidal-Legaz *et al*. 2013), y la sostenibilidad (Martínez-Fernández *et al*. 2013, Banos-González *et al*. 2015, 2016).

Desde la perspectiva de la Dinámica de Sistemas el comportamiento (a veces problemático) de los sistemas complejos, como los SSE, es resultante de la estructura subyacente, la cual se define principalmente por los componentes (o variables) del sistema y las relaciones entre ellos. La complejidad de estos sistemas emerge de relaciones no lineales entre componentes, la existencia de bucles de retroalimentación (i.e. cadenas cerradas de relaciones causa-efecto entre variables) y de retrasos de información y de flujos materiales o energéticos (Vennix 1996).

El proceso de construcción y aplicación de un modelo de gestión según diversos autores, puede clasificarse entre 3 y 7 etapas (Randers 1980, Richardson and Pugh 1981, Roberts *et al*. 1983, Wolstenholme 1990, Sterman 2000, Luna-Reyes y Andersen 2003). La diferencia entre las etapas propuestas se reduce al nivel de agregación o segregación de los pasos metodológicos incluidos en cada una de ellas. Para mejorar el entendimiento de este proceso optamos por dividirlo en tres grandes etapas, especificando los principales pasos dentro de cada etapa (Tabla 1).

Tabla 1. Fases metodológicas para el desarrollo de un modelo dinámico.

Conceptualización	Elaboración del diagnóstico general y definición del problema de estudio.
	Identificación de variables y definición de la hipótesis sobre la estructura del sistema: relaciones y bucles de retroalimentación significativos. Determinación de límites temporales, espaciales y resolución temporal.
	Recopilación, depuración y análisis de datos. Los datos deben ser analizados y revisados con el fin de obtener los valores de los parámetros así como las series temporales acerca de la evolución real de los principales factores integrados en el modelo. Estas series históricas se utilizan tanto para la calibración del modelo como para la formulación de las variables exógenas del mismo.
Elaboración del modelo cuantitativo	Formulación del modelo, especificando todas las ecuaciones y parámetros que intervienen en el modelo.
	Calibración del modelo. Para ello se utiliza un proceso iterativo de calibración en el que los resultados de la simulación para cada variable son comparados con el comportamiento histórico real de la misma.
	Realización de un Análisis de Sensibilidad del modelo dinámico, con el fin de evaluar su robustez, y detectar los parámetros más sensibles (con una mayor influencia en el comportamiento general del sistema) y que deben recibir una especial atención en la aplicación del modelo, incluyendo el análisis de escenarios.
	Verificación del modelo a través de diversos test de validación formal y estructural.
Exploración de escenarios de gestión	Identificación de posibles escenarios futuros e incorporación en el modelo dinámico (los escenarios pueden implicar cambios estructurales, cambios en las condiciones de contorno o cambios cuantitativos en los parámetros internos del sistema).

La Dinámica de Sistemas y los modelos de simulación dinámica orientados a la gestión se configuran, por tanto, como una aproximación teórica-metodológica idónea para el estudio de los SSE, y como una herramienta de apoyo para guiar los procesos de transición hacia la sostenibilidad de estos sistemas. Su aplicación puede además contribuir significativamente a cubrir algunas de las lagunas críticas todavía existentes, como la necesidad de comprender desde enfoques formales y cuantitativos la evolución de los SSE a lo largo del tiempo, cómo estos sistemas se ven afectados por los cambios ambientales y socioeconómicos de escalas superiores, y cómo responden a las intervenciones políticas (Young *et al*. 2006, Carpenter *et al*. 2012, Allen 2014).

1.4. El sistema de estudio: el oasis de Los Comondú (Baja California Sur, México)

Los oasis de Baja California Sur (BCS) son SSE tradicionales. Estos oasis son enclaves donde perdura la cultura ranchera sudcaliforniana, la cual se considera fruto de la unión entre la cultura indígena bajacaliforniana y la cultura occidental mediterránea, llevada por los jesuitas españoles y sus colonos en el siglo XVIII. Esta cultura se ha caracterizado históricamente por la austeridad, la autosuficiencia y el aprovechamiento variado e integral de la diversidad biótica (Cariño, 2001, Cariño *et al*. 2016). Los oasis representan menos del 1% de la superficie total de BCS, sin embargo, son sustento y refugio de una gran diversidad de especies de fauna y flora (algunos de ellos endémicos) y reservorios de carbono por contener una de las biomasas forestales más densas de la región. Además, tienen una gran importancia en el control de inundaciones, así como en la retención y exportación de sedimentos y nutrientes (Arriaga y Rodríguez Estrella 1997, Cariño *et al*. 2016). Estos oasis fueron por más de un siglo los ejes centrales del desarrollo socioeconómico y cultural de BCS. La actividad económica estaba basada principalmente en la agricultura de regadío tradicional, complementada con la ganadería extensiva, para el caso de los oasis serranos, y con la pesca, para el caso de los oasis costeros. Sin embargo, desde mediados del siglo XX, la modernización de la economía de BCS y su integración en el proceso de globalización, ha despojado a estos SSE de su centralidad e importancia tradicionales, por lo que ahora se encuentran amenazados. El modelo de desarrollo regional de BCS ha fomentado a grandes rasgos el abandono y deterioro de las áreas que tenían una mayor disponibilidad natural de agua y de suelos aptos para el cultivo, las cuales han sido sustituidas por esquemas de producción agrícola altamente dependientes de insumos externos (bombeo de aguas subterráneas, pesticidas y fertilizantes) y la dedicación de la tierra a fines turísticos costeros. La salinización de aguas subterráneas y suelos por la sobreexplotación de los acuíferos en los grandes valles agrícolas agroindustriales de la región, el crecimiento urbano incontrolado, la marginación y la pobreza en la periferia

El oasis de Los Comondú es uno de los oasis más representativos y mejor conservados de BCS. Tiene una de las más diversas mezclas de especies cultivadas perennes de todos los oasis de la península (de Grenade and Nabhan 2013). Este oasis se ubica en la parte media de la Sierra de La Giganta, dentro del municipio de Comondú (Figura 4). Desde 2008 está incluido como Sitio Ramsar bajo el nombre de Humedal de Los Comondú. A diferencia de otros oasis, como los costeros, este oasis ha permanecido al margen de inversiones para el desarrollo de complejos turísticos y residencias secundarias. Hasta el año 2011, el oasis de Los Comondú estaba pobremente conectado con la carretera transpeninsular que une los núcleos urbanos más importantes de la entidad, lo que influye fuertemente en la economía y dinámica poblacional de las áreas rurales (Collantes 2007). Quizá uno de los frutos de ese aislamiento haya sido la buena conservación de este SSE tradicional. Estudios recientes sobre fauna listaron un total de 126 especies (89 aves, 15 mamíferos, 3 anfibios y 25 reptiles). El 31% de las especies no han sido citadas en los oasis próximos, el 13,5% son endemismos, y el 30,5% están listadas bajo alguna categoría de protección de la NOM-59-SEMARNAT-2010 (Pérez-García *et al*. 2013). Sin embargo, el deterioro del tejido social, la quiebra de las instituciones locales, y el fuerte éxodo rural que ha vivido en los últimos 70 años amenazan con colapsar este SSE tradicional en el medio-largo plazo.

Figura 4. Mapa de ubicación del área de estudio dentro del estado de Baja California Sur, México.

Preocupados por la trayectoria de los oasis sudcalifornianos y con el afán de contribuir a revalorizarlos, hace diez años, un equipo interdisciplinar de científicos de México, Estados Unidos y España, se unieron en la "Red Interdisciplinaria para el Desarrollo Integral y Sustentable de los Oasis Sudcalifornianos" (RIDISOS). Un pequeño proyecto financiado por la Agencia Española de Cooperación Internacional para el Desarrollo, "Modelado dinámico de los sistemas de oasis de Baja California Sur. Bases conceptuales y metodológicas" permitió sentar las bases para el proyecto de ciencia básica de Consejo Nacional de Ciencia y Tecnología (CONACyT) de México "Conocimiento, valoración y desarrollo sustentable de los oasis sudcalifornianos", que desarrolló entre 2009-2012 una investigación centrada en el oasis de Los Comondú como caso de estudio piloto y cuyo objetivo fue hacer un diagnóstico integral de su estado actual y una descripción de su evolución histórica (Cariño *et al*. 2013). Este proyecto fue continuado entre 2014-2016 con el proyecto "Gobernanza de la Biodiversidad" (GIZ-CONABIO), de carácter aplicado y dirigido a la organización y búsqueda de alternativas de desarrollo mediante talleres participativos con los principales actores involucrados (ej. la población local del oasis, el gobierno de BCS y la RIDISOS). La presente tesis forma parte de los resultados de esta investigación a largo plazo sobre el SSE del oasis de Los Comondú.

El estudio en profundidad de las causas estructurales del declive del oasis de Los Comondú, el análisis de los efectos que los cambios ambientales y socioeconómicos a escalas regional y global tienen sobre su dinámica, y la identificación de las potenciales áreas de intervención más sensibles de este sistema, son factores que pueden mejorar enormemente el conocimiento sobre el sistema y su dinámica. Desde este conocimiento generado, y con la consecuente movilización y participación activa de los principales actores locales o stakeholders, se puede contribuir de manera más efectiva en la planificación de estrategias de gestión futuras y apoyar los procesos de toma de decisiones, encaminadas a revitalizar este sistema, mejorar la calidad de sus habitantes, y gestionar la resiliencia dentro de dinámicas sostenibles. La presente tesis, por tanto, además de poder contribuir al conocimiento, por constituir uno de los primeros estudios a largo-plazo cuantitativos de este tipo sobre un SSE tradicional a escala local, puede ser un ejemplo de aproximación teórica y metodológica replicable para otros SSE tradicionales.

1.5. Objetivos y estructura de tesis

La presente tesis tiene como objetivo general estudiar desde una perspectiva sistémica las causas estructurales del declive de un sistema socioecológico tradicional, afectado por el proceso de cambio global, y en base a este conocimiento, evaluar medidas de gestión que puedan ayudar a frenar y revertir el declive de este sistema y contribuir a su gestión sostenible.

Específicamente, y en concordancia con la línea metodológica planteada, se plantean tres objetivos:

1. Conceptualizar el sistema de estudio, y construir un modelo cualitativo como hipótesis estructural explicativa del comportamiento histórico observado.

2. Construir y validar el modelo cuantitativo que simule el comportamiento histórico del sistema, y analizar los efectos de las variables externas sobre la dinámica endógena del sistema.

3. Identificar los puntos más sensibles del sistema que podrían ser intervenidos a través de medidas de gestión, y evaluar el efecto de estas potenciales intervenciones en la dinámica del sistema.

La tesis se estructura en tres capítulos, los cuales abordan los objetivos específicos planteados.

En el **Capítulo 1**, se detalla el proceso de conceptualización del sistema de estudio. A través de técnicas de investigación social, la participación de un equipo multidisciplinar de expertos, la revisión bibliográfica, y las estadísticas oficiales, se construye un modelo cualitativo que explica el comportamiento problemático observado en el sistema. El resultado de este capítulo es el establecimiento de la hipótesis estructural (variables e interrelaciones del sistema) responsables de la dinámica observada, y un conjunto de hipótesis dinámicas sobre los efectos de las variables externas sobre el sistema. Este trabajo, publicado en la revista *Ecology and Society*, constituye la base sobre la que se desarrollan los siguientes capítulos.

En el **Capítulo 2**, se describe el modelo cuantitativo y se muestran los resultados de la simulación de referencia de las principales variables del sistema, así como los resultados de las pruebas de validación formales. Para la evaluación de los efectos de las variables externas sobre la dinámica endógena, se diseñan una serie de simulaciones experimentales que permiten cuantificar el peso de cada una de estas variables en la dinámica del sistema e identificar las sinergias y trade-offs que se producen entre ellas. En este capítulo se comprueban las hipótesis planteadas en el Capítulo 1. Este trabajo, enviado a la revista *Global Environmental Change*, constituye uno de los primeros estudios que analiza cuantitativamente el declive de un sistema socioecológico de pequeña escala, el efecto que sobre la dinámica endógena

En el **Capítulo 3**, partiendo del modelo de simulación dinámica validado en el capítulo anterior, se identifican los parámetros más sensibles del modelo a través de un análisis de sensibilidad. Estos parámetros más sensibles del sistema, representan potenciales puntos de palanca que pueden provocar cambios cualitativos en la dinámica del sistema con un menor esfuerzo. Por medio de la simulación de escenarios futuros, se evalúan los efectos de estas potenciales intervenciones en la dinámica del sistema. Los resultados de estos análisis son comparados con las medidas de gestión propuestas por los principales actores o stakeholders (la población local, el gobierno regional de Baja California Sur y la academia). Se analiza el grado de convergencia y divergencia de las propuestas de los actores con respecto a los potenciales puntos de palanca identificados, y las diferencias entre ellos. Los resultados de este trabajo, enviado a la revista de *Frontiers in Ecology and the Environment*, representan la etapa más avanzada de este trabajo a largo plazo y, junto a la exploración futura del conjunto de medidas de gestión propuestas por los principales actores, constituye una base de apoyo para procesos de toma de decisión.

Por último, se muestran las principales conclusiones derivadas de la presente tesis.

CAPÍTULOS

*Llano de San Julio (fotografía de Andrés Giménez Casalduero)

CAPÍTULO 1

*Huerta a principios del siglo XX (fotografía cedida por Fredderick J. Conway, y obtenida de Óscar Aguiar Meza)

Understanding the decline and resilience loss of a long-lived social-ecological system: insights from system dynamics

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Abstract

Collapse of social-ecological systems (SESs) is a common process in human history. Depletion of natural resources, scarcity of human capital, or both, is/are common pathways toward collapse. We use the system dynamics approach to better understand specific problems of small-scale, long-lived SESs. We present a qualitative (or conceptual) model using the conceptualization process of the system dynamics approach to study the dynamics of an oasis in Mexico that has witnessed a dramatic transition to decline in recent decades. We used indepth interviews, participant observation, expert opinions, and official statistical data sets to define the boundaries, and structure in a causal loop diagram of our studied system. We described historical trends and showed the reference mode for the main system variables (observed data), and analyzed the expected system behavior according to the system structure. We identified the main drivers that changed the system structure, as well as structural changes, and the effects of these changes on the dynamics, resilience, and vulnerability of this SES. We found that the tendency of this SES toward collapse was triggered by exogenous factors (growth of modern agriculture in nearby valleys, and socio-political relocation), and was maintained by an endogenous structure. These structural changes weakened the resilience of this SES. One of these changes resulted in a long-term maladaptation of the SES, which increased its vulnerability to frequent system disturbances (hurricanes and droughts). The conceptual model developed provides an in-depth qualitative description of the system, with an important amount of qualitative and quantitative information, to establish the structural hypothesis of the observed behavior. Using this qualitative model, the next research steps are to develop a quantitative model to test the qualitative theories, and to explore future scenarios of system resilience for decision-making processes to improve local conditions and restore the well-functioning of the system.

Key Words: collapse; depopulation process; feedbacks; maladaptation; oasis of Comondú; qualitative model; system structure

INTRODUCTION

Civilizations, societies, and cultures have lived boom–bust cycles throughout human history (Turchin and Nefedov 2009). Depletion of natural resources, scarcity of human capital, or both, is/are common pathways toward collapse (Motesharrei *et al*. 2014). This is consistent with insights into complex adaptive systems and the resilience paradigm by means of adaptive cycles (Holling 1987, 2001, Abel *et al*. 2006, Walker *et al*. 2006), where the collapse of social-ecological systems (SESs) is usually preceded by loss of (social, human, natural, physical, and/or financial) capital, and loss of resilience. According to historical social changes, the best-known drivers that can lead to the collapse of SESs are population growth, technological change, resource degradation, catastrophes, trade, war, and competition both within and between societies (Cocks 2003). Be it generalized, the ecological strain (use of natural resources) and economic stratification (wealth distributed in society) are indicated as the common factors that can lead to complete collapse (Motesharrei *et al*. 2014). Some of these drivers might belong to the system itself (as endogenous factors), such as demographics changes, wealth distribution, or use of natural resources. However, others remain outside the system (as exogenous factors) and are related to changes on higher scales that affect internal dynamics (e.g., socioeconomic changes, natural disasters, technological change). A better understanding of the relationships between changes on higher scales with changes in the structure and dynamics of SESs is needed to better address their specific problems, and to comprehend their changes on adaptability, resilience, and vulnerability (Young *et al*. 2006).

While some general theoretical models have been successfully developed to understand SESs dynamics that lead to collapse (Brander and Taylor 1998, Anderies 2000, Motesharrei *et al*. 2014), addressing the case-specific study of SESs has received less attention. Most of these case studies rely on the adaptive cycles theory (Baral *et al*. 2010, Urgenson *et al*. 2010, Vang Rasmussen and Reenberg 2012). Although this approach is useful for recognizing changes in system behavior, an adaptive cycle is not predictive, and theoretical phases are not necessarily sequential and cannot explain causes and effects in particular cases because they are relatively abstract (Abel *et al*. 2006). The system dynamics approach can be a useful methodological alternative because it focuses on the structural causes of the problematic behavior of the systems, deepening into causal and feedback relationships (Roberts *et al*. 1983, Vennix 1996, Sterman 2000, Jørgensen and Bendoricchio 2001). Knowing the structural causes of specific problems could efficiently support decision-making processes about management alternatives that promote the well-functioning and conservation of SESs (Costanza and Ruth 1998), especially if we wish to move away from panaceas that frequently fail (Ostrom *et al*. 2007).

The system dynamics approach has been widely used in the study of SESs, and has focused on different topics, such as sustainability (Saysel *et al*. 2002, Lacitignola *et al*. 2007, Tomlinson *et al*. 2011, Li *et al*. 2012, Martínez-Fernández *et al*. 2013, Vidal-Legaz *et al*. 2013, Banos-González *et al*. 2015, 2016), water management (Xiao-Qing *et al*. 2012, Sanga and Mungatana 2016), changes in land use (Dale *et al*. 1993, Duffy *et al*. 2001, Evans *et al*. 2001, Portela and Rademacher 2001, Marín *et al*. 2012, Baur and Rinder 2015), and effects of resource management and social practices on wildlife (Musacchio and Grant 2002, Bueno and Basurto 2009, Pérez *et al*. 2012). However, currently there are no studies focused on the causes of decline of small-scale, long-lived SESs. Many of these small-scale, long-lived SESs are local communities that rely on family farming. Family farms manage about 70–80% of the world's agricultural land, and produce more than 80% of the world's food (FAO 2014). Therefore, these systems play a key role not only in the sustainable use of natural resources but also in food security. Preserving long-lived SESs helps maintain institutional diversity, which implies a rich set of solutions of social systems by adapting to the ecological and socioeconomic context. This is a critical point if we consider that a collection of many small-scale SESs may better address environmental problems on a global scale than a smaller number of larger scale nation states (Janssen *et al*. 2007).

We use the system dynamics approach to study the structural causes responsible for the dramatic transition from well-functioning to decline of a small-scale, long-lived SES—the oasis of Comondú in Baja California Sur (BCS), Mexico. The oasis of Comondú is one of the largest oases of BCS. We present the conceptual model of this SES. This initial step of system dynamic modeling is an iterative process, which requires the most time and effort. By itself, it is a useful and qualitative branch of system dynamics (Wolstenholme 1990, Coyle 2000). However, and more importantly, it is considered a necessary step to quantitative modeling because it allows visualization of the modeler's concepts and the system hypothesized structure related to the observed behavior (Jørgensen and Bendoricchio 2001).

We used in-depth interviews, participant observation, expert opinions, and official statistical data sets to build a conceptual model to better understand the causes and effects and the endogenous or exogenous factors that have dangerously modified the system structure and behavior. For this purpose, we qualitatively analyzed the structure (variables, relationships, and feedbacks) of this SES. We located the transition point from well-functioning to decline in time. We also identified the main drivers of this behavioral change in relation to structural changes (are these drivers endogenous, exogenous, or both?). Finally, we explored system changes and their impact on the system's resilience and vulnerability. As far as possible, we included quantitative data derived from statistical data sets and in-depth interviews in order to quantitatively characterize the system (parameters and data needed for quantitative modeling, and observed data needed in future model evaluation). We found that exogenous drivers triggered the decline of our studied SES, but the endogenous structure has also maintained the system in this undesirable state. The resilience has been reduced and the structural changes have made the SES more vulnerable to historical frequent disturbances (e.g., hurricanes). The conceptualization process of the system dynamics approach has provided a profound qualitative understanding of the system structure and the main causes that pulled the system dynamics toward decline. It has allowed us to collect qualitative and quantitative data needed in future modeling steps. In addition, it has contributed to building a strong confidence relationship with local actors, which could support possible future participatory processes. This is a first step to formalizing a quantitative computational model that could support decision-making processes for improving local conditions and restoring the system's well-functioning.

METHODS

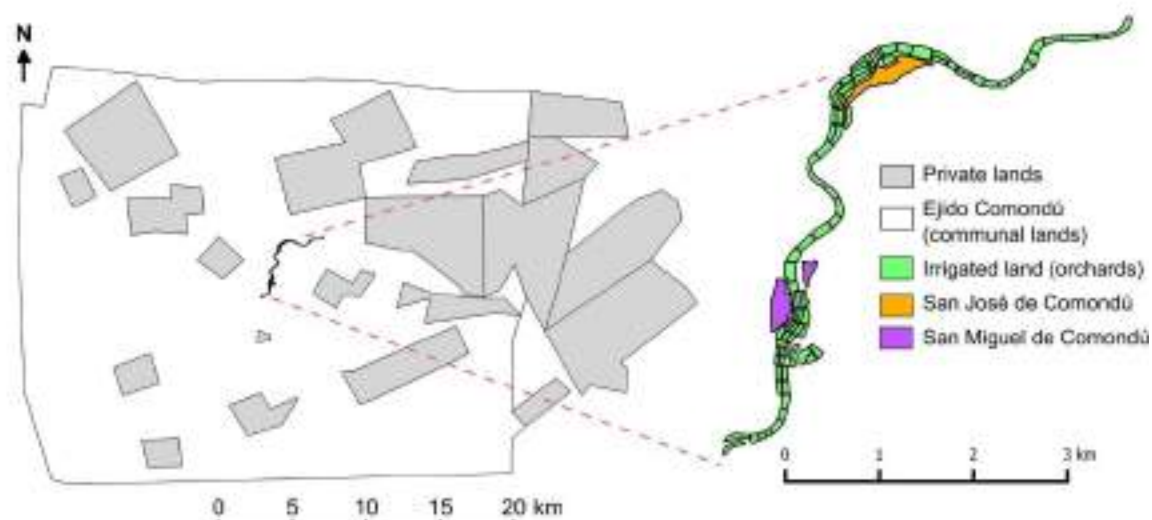
The study area: the oasis of Comondú

In Baja California Sur, Mexico, under pronounced isolation and aridity conditions, oases are the most important long-lived, small-scale SESs, especially when we consider the biodiversity, history, and culture of this region (Arriaga and Rodríguez-Estrella 1997, Cariño *et al*. 2013, Cariño and Ortega 2014). After the Jesuits arrived in the late 17th century, natural wetlands were transformed into cultural landscapes, similar to those in northern Morocco and Spain. The indigenous culture and the western Mediterranean culture joined to form a society that was characterized by austerity, self-sufficiency, and the comprehensive use of biological diversity (Cariño 2001). In all the oases of BCS, traditional irrigated agriculture was successfully practiced, and was supplemented by fishing in coastal zones and by livestock in mountain regions.

The oasis of Comondú is one of the largest and best ecologically preserved oases of BCS. It has been a RAMSAR site since 2008, and is currently in the process of forming part of the Sierra de La Giganta y Guadalupe Biosphere Reserve. It is located 130 km from Ciudad Constitución, the municipality seat (Fig. 1), in the Sierra de La Giganta mountain range, and is poorly connected to other nearby villages or towns, like Loreto. The area under study comprises 107,080 ha (Fig. 2), which includes 80 ha of irrigated land, 70,000 ha of communal land, and 37,000 ha of private land in the immediate surroundings; the last two large areas are devoted to ranching. Most inhabitants live in the communities of San José de Comondú and San Miguel de Comondú, both located in a canyon hat is 16 km long and 50–500 m where the irrigated land is also located (Fig. 2). The remaining inhabitants live on ranches with homes sited around temporary ponds and streams in the immediate surroundings.

Fig. 1. Location of the oasis of Comondú.

Fig. 2. The study area with details of the irrigated land and local communities.



The area belongs to the Sonoran Desert. Rainfall is distributed during two main periods. One period coincides with the hurricane season in the Pacific (from mid-May to the end of November) and involves 70% of the annual rainfall. The other period, commonly known as "equipatas," takes place between November and January, and represents 21% of the annual rainfall. Extreme weather events like hurricanes and droughts are frequent in this region. Average annual rainfall is 175 mm, and temperature oscillates between 10º and 36ºC, with an average of 23ºC (Tenza *et al*. 2013).

The system dynamics approach, qualitative data, and qualitative models

System dynamics allowed us to analyze world problems from a comprehensive point of view by focusing on the structure and dynamics of complex systems. The source of this complexity was nonlinear relationships between system components, feedback, and material or information delays. Jay W. Forrester developed system dynamics in the 1950s, and he applied this methodology to industrial problems (Forrester 1958, 1961). His success in analyzing industrial business cycles extended the use of system dynamics to other fields, like urban problems (Forrester 1969) and global problems (Meadows *et al*. 1972, 1974, Forrester 1973). System dynamic modeling has proved particularly useful for studying complex systems like SESs (Roberts *et al*. 1983, Costanza and Ruth 1998, Martínez-Fernández *et al*. 2000, Pérez *et al*. 2012, Banos-Gonzalez *et al*. 2015, Turner *et al*. 2016).

Building management models is one of the applications of the system dynamics approach (Vennix 1996). It assesses alternative management options and supports decision-making processes to solve specific problems, and stems from a profound understanding of the system structure. Building a management model is an iterative and a continuous learning process about the system, which could be divided into three main phases: (1) conceptualization and qualitative modeling, (2) quantitative modeling, and (3) exploring future scenarios. Despite the mathematical character associated with the procedure, it is also recognized that most information available to the modeler is qualitative (Forrester 1992, Luna-Reyes and Andersen 2003). As suggested by Forrester (1992), the available information declines (in many orders of magnitude) from mental to written information, and again from written to numerical information. Although it could have a role in quantitative modeling, model evaluation, or exploration of alternative management options, the greatest amount of qualitative information is used in the conceptualization stage (Forrester and Senge 1980, Randers 1980, Richardson and Pugh 1981, Wolstenholme 1990, Coyle 2000, Sterman 2000, Luna-Reyes and Andersen 2003). We focus on this first stage, which is critical, because it provides a profound qualitative understanding of the system's functioning (Vennix 1996, Downing *et al*. 2014), allows us to visualize the system's hypothesized structure, and establishes the basis for the construction of the quantitative dynamic simulation model (Jørgensen and Bendoricchio 2001).

Qualitative models are the result of conceptualizing the problem under study. We specified "problem" rather than system because it helps delimit the study in time and space, and helps determine the elements that form part of the model. Delimitation of real systems is difficult given their complexity. Identifying a problematic behavior is a key issue for determining the variables and relationships involved (Vennix 1996). The problematic behavior perceived from empirical knowledge and observed data is the reference mode. The consistency between model behavior and the reference mode is one of the factors that enhances trust in the developed model (Vennix 1996, Solecki and Oliveri 2004, Happe 2005, Bert *et al*. 2011, Martínez-Fernández *et al*. 2013).

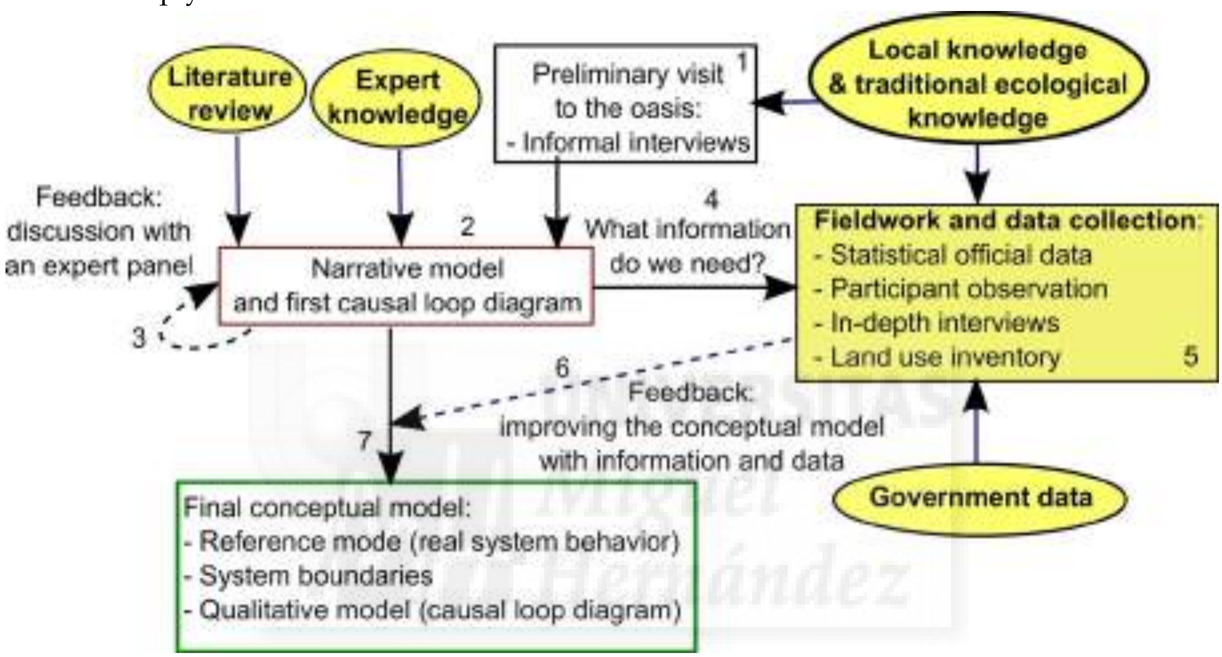
Qualitative models are often represented by causal loop diagrams, which include the main system variables linked to the problematic behavior, the connections between these variables by means of arrows, and the sign of these interactions (i.e., positive or negative). A relationship is positive when an increase in the value of a variable brings about an increase in the other (i.e., both variables change in the same direction). In contrast, a relationship is negative when an increase in the value of a variable leads to a decrease in the other (i.e., the variables change in opposite directions). Feedback loops are composed of two variables or more that are involved in a closed chain of a cause-and-effect relationship. By multiplying the signs of the relationships involved in feedback, we determine the overall loop sign. Positive feedback loops represent reinforcing processes (either an increase or a decrease), and do not tend to equilibrium. These cycles will continue in the direction of their momentum until an external factor intervenes and breaks the cycle. When they have favorable results (like growth), they are known as "virtuous cycles," but when they have detrimental results (like development trap), they are known as "vicious cycles." In contrast, negative feedback loops represent self regulatory processes that tend to stabilize dynamics. The variables that affect system dynamics, but are not influenced by it, are external variables or forcing functions (e.g., climatic and socioeconomic factors like rainfall, market prices).

Qualitative models represent the hypothesis about the system structure and behavior (i.e., the response to "What structure is responsible for the observed behavior?"). They allowed us to analyze the system's structural changes. Among these changes, we found (1) a change in the relative weight of the different interactions, (2) a change in the sign or the direction of relationships or loops, and (3) the addition or removal of interactions (Downing *et al*. 2014).

Conceptualization process and reference mode building

The conceptualization phase was an iterative process with five main sources of information: (i) scientific literature, (ii) expert opinion, (iii) local and traditional ecological knowledge, (iv) government data, and (v) fieldwork. This process is outlined in Fig. 3.

Fig. 3. The conceptualization process. Numbers indicate the order of the methodological steps. The main information sources are marked in yellow. Dashed lines imply information feedback.



In 2009, we reviewed the available scientific literature about oases of Baja California Sur, but specific information about the oasis of Comondú was scarce. We made a first visit to the oasis in 2009, where we conducted informal interviews with local inhabitants. A workshop was conducted then, where we gathered the expert opinions of scientific researchers from a network called RIDISOS (Appendix 1) (a Spanish acronym that stands for "Interdisciplinary Network for Integral and Sustainable Development of the Oasis of Baja California Sur") to initially define the main problem. After processing the information, in 2010 we built the first conceptual model in a narrative form, which means that we wrote a description of the history of the oasis and the behavior of the main items of the system (social-demographic factors, economic and productive activities, and the main external factors that have affected the system). This narrative model was accompanied by a first extensive causal loop diagram. Corrections, suggestions, and comments were added telematically by RIDISOS members to reach a consensus about the system's problematic behavior, system boundaries, and its elements (variables, relationships, and the signs of relations). Once the main variables were identified, we began fieldwork to improve our knowledge about the system and to obtain historical data series to build the reference mode. During the 2010–2012 period, we went on four stays that lasted from 15 days to 4 months. Data sets of climate, population, and market prices were obtained from different government agencies in Mexico. However, the small scale of the case study hindered the collection of data about production activities (e.g., farmlands in production, production volumes). To obtain household-type information, we conducted a participant observation during 5 weeks, and 52 in-depth interviews with 43 interviewees (Table 1). The people interviewed were selected by snowball sampling; 24% were women, and the average age of the interviewees was 49 years. The main topics of the interviews were life conditions over time, problems and characteristics of the rancher system, sale of livestock products with and without intermediaries, problems and characteristics of irrigation systems, and the life story of emigrants who left the oasis in recent decades (Appendix 2). All the interviews were transcribed, and the interviewees' experiences and impressions obtained through observation were registered in notebook diaries. Both methods—participant observation and interviews—are recognized social research techniques that are especially useful in the conceptualization process (Luna-Reyes and Andersen 2003). The interview is the more widely used method, but if time and resources permit, the participant observation is the most complete form of sociological datum (Becker and Geer 1957). The participant observation is the method in which the observer (the researcher) participates in the daily life of the people under study. This method allows the observer to more deeply understand the relationships between the people under study; to unearth personal motivations, interests, and conflicts; to detect the personal distortions of reality; and to raise awareness and sensitivity about many problems that would be overlooked in interviews. In addition, it reduces the error associated with the interpretation of the words used by interviewees (Becker and Geer 1957).

We made a land use inventory to characterize the dynamics of irrigated land. This allowed us to know the areas with production and the state of orchards. In the same way, we counted and located the number of occupied and abandoned ranches with the support of satellite images (Google Earth, DigitalGlobe). The historical data of land use (e.g., year of abandonment, crops, users), and dynamics of occupancy and abandonment of ranches were collected through interviews with key informants.

In-depth interviews and participant observation were essential to improve and enrich the initial conceptual model. The qualitative and quantitative information derived from the interviews was used to construct the reference mode (especially for the economic and productive activities-related variables), and to define parameters that will be needed in the next step of quantitative modeling (see a summary of quantitative data in Appendix 3). Official statistical data sets and the land use inventory results were used primarily to build the reference mode of the main model variables. The regional market prices of the main agricultural and livestock products of the oasis were converted from current prices into constant prices to avoid inflation effects. We used Fisher's price index, with 1975 as the base year, for a set of agricultural and livestock products of BCS during the study period. The results presented herein show the final conceptual model after two improvement cycles.

Table 1. List of in-depth interviews classified by topic. The column (n) indicates the number of interviewees, (N) depicts the number of potential interviewees according to the target population, and (ni/Ni) denotes the percentage of the ratio between interviewees and the potential interviewees for each topic.

Topic	Target population	Type	n	n_i/N_i(%)
Life in the communities of the oasis of Comondú and dynamics of irrigated land	Landowners in irrigated lands	In depth-interview	24	33.8
Livestock activity	Families with ranches	In depth-interview	19	39.6
The role of intermediaries of livestock products	Intermediaries	In depth-interview	2	100
Life story and opinion of the emigrants of the oasis of Comondú	Emigrants of Comondú (1940-2000)	In depth-interview	7	0.38†

† Percentage that estimates emigrants from data of total population, births and deaths.

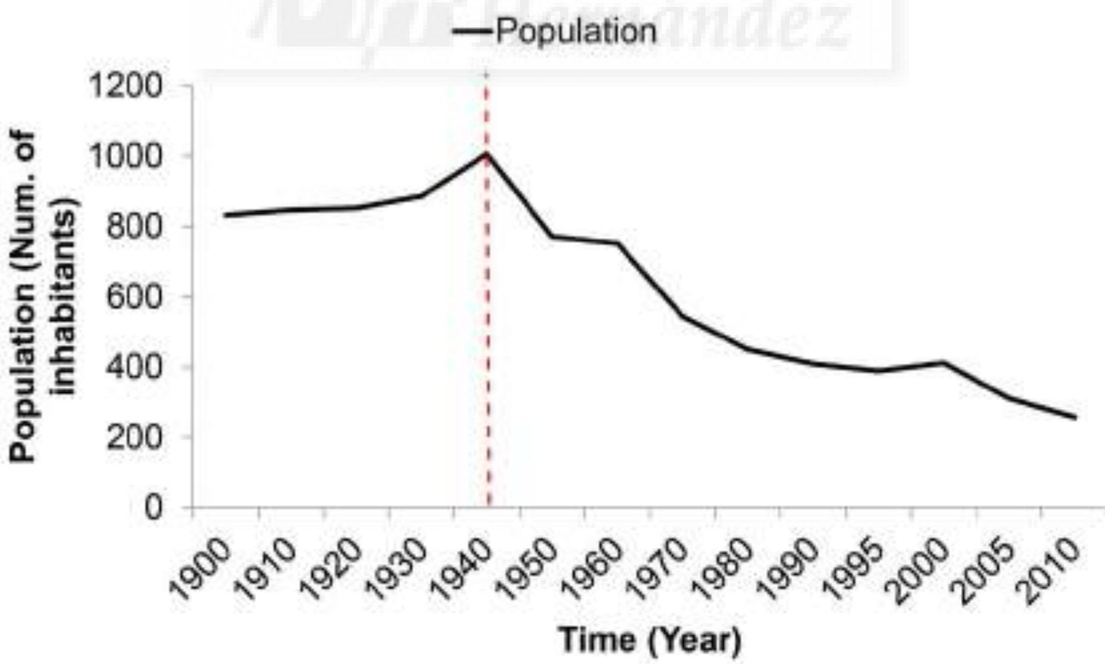
RESULTS

Due to the cyclicity of the conceptualization process, the methods and results were interrelated. Defining the system boundaries, studying historical data, and building the reference mode and the causal loop diagram therefore formed part of both the methods and results. Improvement in one of these tasks led to changes and improvements being made in other tasks. However, in order to facilitate their presentation, we first defined the system boundaries and presented the SES structure in a causal loop diagram, and analyzed the system's feedback loops to explain expected system behavior according to the system structure. We described historical trends and showed the reference mode for the main system variables (observed data). Finally, we identified the main drivers that changed the system structure, as well as structural changes, and the effects of these changes on the dynamics, resilience, and vulnerability of the SES of the oasis of Comondú.

System boundaries and the underlying social-ecological system structure

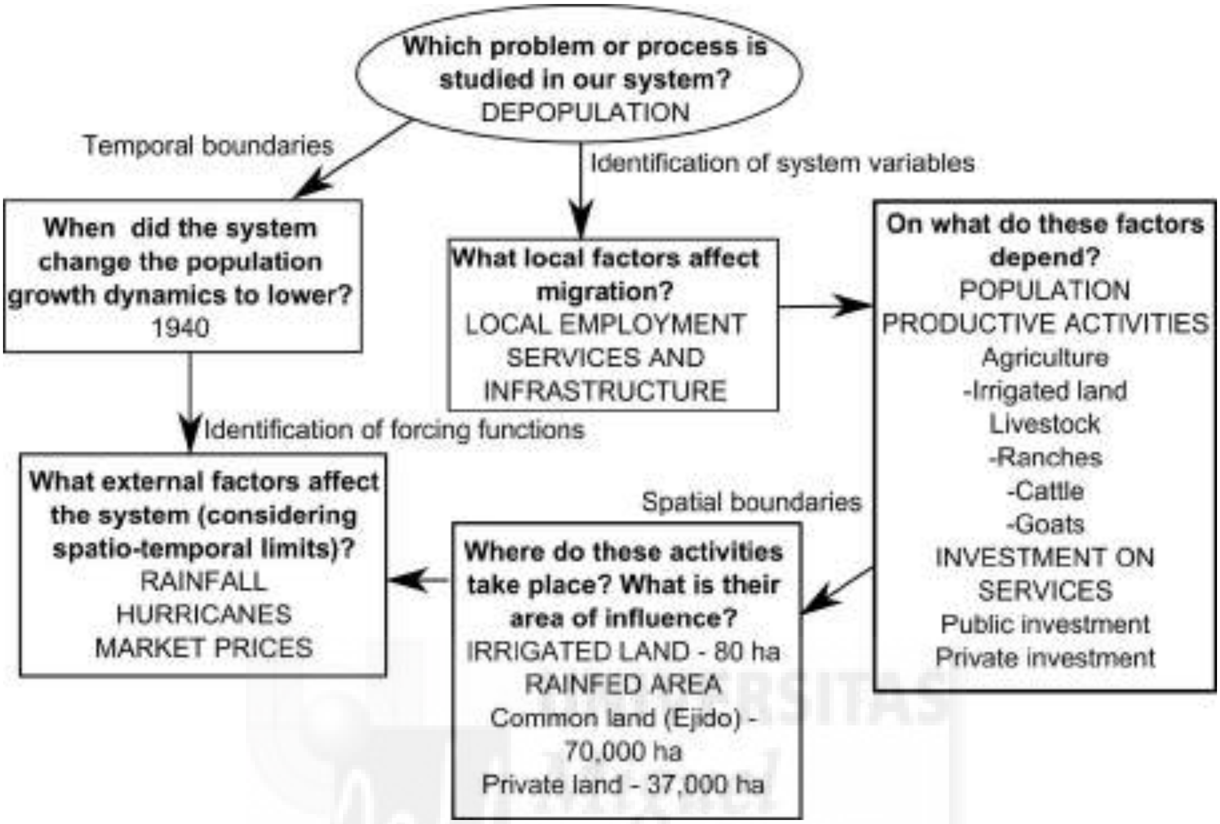
The oasis of Comondú changed dynamics from well-functioning to declining. The population dynamics is the system variable that best reflects this tendency (Fig. 4). To analyze the causes and effects, we selected the piece of reality associated with problematic behavior: the depopulation process (Fig. 5). From 1900 to 1940, the trend moved toward growth. Yet from that point, the trend moved toward decline. Ideally, the time boundary should begin years before this turning point. Due to data scarcity for these years, our time horizon started in 1940. Spatial boundaries included the area of local communities (San José and San Miguel of Comondú), and the area used for their production activities (agriculture on irrigated lands and livestock on rangelands). We identified the main population dynamics variables, which in this case, strongly relied on the availability of local employment, services, and infrastructure. Likewise, these factors depended on the productive activities and economy of the oasis. Three main forcing functions (or external conditions) affected system dynamics: market prices, rainfall, and hurricanes. The qualitative model showed the relation between system variables and the effects on population dynamics (Fig. 6).

Fig. 4. The oasis of Comondú population (1900–2010). The red dashed line indicates the turning point. Source: population and housing censuses of the Mexican National Institute of Statistics and Geography (INEGI 2011).



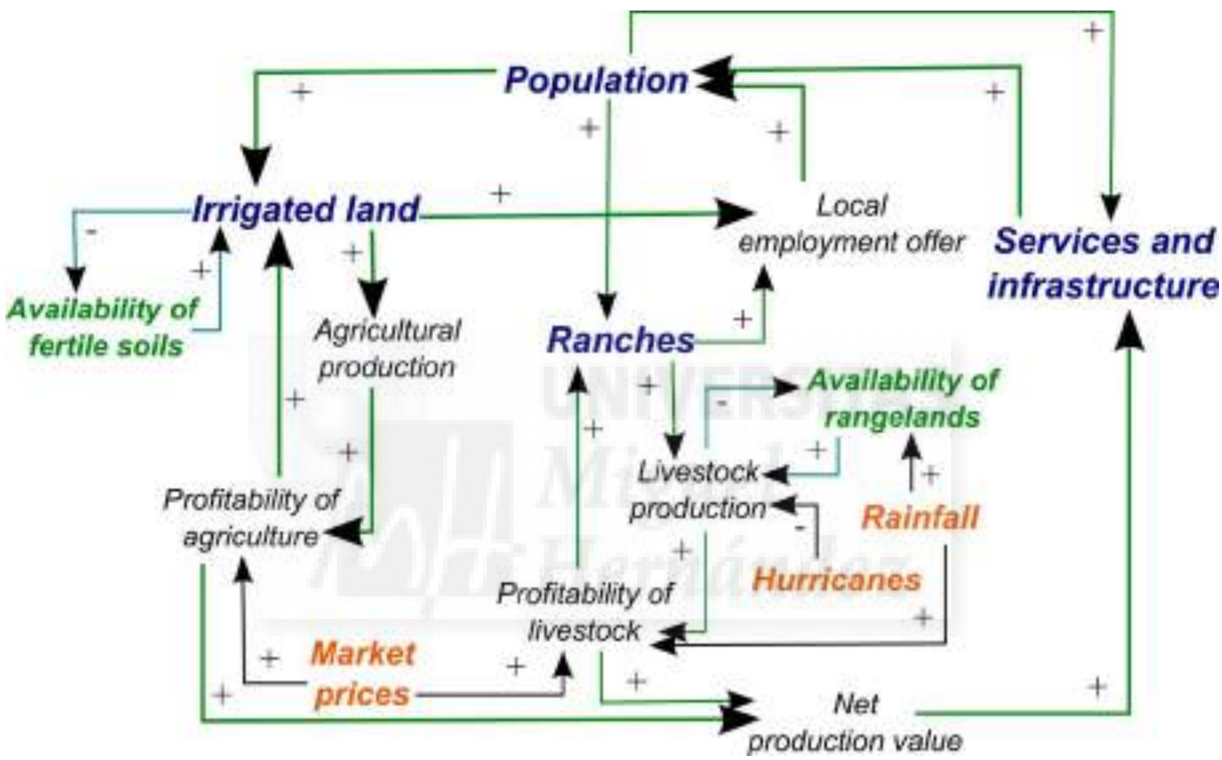
We identified nine feedback loops in the system structure (Table 2), of which seven were positive and two were negative. There was a direct positive feedback loop between population and services and infrastructure in relation

Fig. 5. Defining system boundaries and components. The sketch summarizes the main issues to define the system, starting from the observed problem.



to the maintenance of these services with human capital. Services and infrastructure represents public services (education, health, security, transportation, communication) and private services (local shops, professional skills, community works), physical infrastructure (irrigation canals, dams, urban furniture), and social infrastructure (local institutions). Each productive activity (agriculture and livestock) was embedded in a virtuous cycle that led to economic growth. The more irrigated land in production and the more occupied the ranches, the higher the production (agricultural production and livestock production) and profitability (profitability of agriculture and profitability of livestock), which encourages an increase in the amount of irrigated land and the number of ranches. This growth trend was also supported by two additional positive feedback loops per productive activity. One was linked to the local employment offer, and the other to services and infrastructure. As the amount of irrigated land (hectares in production) and the number of ranches increased, the local employment offer also increased, which led to an increase in population. As the population became larger, the need to increase the amount of irrigated land and the number of ranches in production also grew, which brought about increased agricultural production and livestock production. Consequently, the net production value rose, which led to more investments in local services and infrastructure, which attracted a larger population. As before, population growth led to an increase in the amount of irrigated land and the number of ranches in production.

Fig. 6. The causal diagram of the underlying system structure. The diagram and the feedback loops are explained in the text. The main variables of the system are marked in blue with larger letters. Environmental limits are depicted in green. The external conditions or forcing functions are marked in orange. Blue arrows are negative feedback loops. Green arrows are positive feedback loops (virtuous cycles). The feedback loops associated with agriculture are larger because they have a heavier relative weight.



There were two negative feedback loops, and both were related to environmental constraints. As the amount of irrigated land in production increased, the availability of fertile soil declined. With less availability of fertile soil, the capacity to increase the amount of irrigated land in production declined. Likewise, as livestock practice (livestock production) increased, the availability and quality of rangelands to support grazing (availability of rangelands) decreased.

Market prices varied the profitability of agricultural and livestock products. Rainfall changed the carrying capacity of rangelands, which represented the area required to support livestock without damaging natural resources. The carrying capacity declined as rainfall decreased. Therefore, drought periods resulted in sharp decreases in livestock production (cattle and goats). Hurricanes, the other extreme weather event, also affected livestock production by increasing livestock mortality.

Table 2. Feedback loops and their signs.

Loop	Sign
Population + Services and infrastructure + Population	+
Irrigated land + Agricultural production + Profitability of agriculture + Irrigated land	+
Ranches + Livestock production + Profitability of livestock + Ranches	+
Irrigated land + Local employment offer + Population + Irrigated Land	+
Ranches + Local employment offer + Population + Ranches	+
Irrigated land + Agricultural production + Net production value + Services and infrastructure + Population + Irrigated land	+
Ranches + Livestock production + Net production value + Services and infrastructure + Population + Ranches	+
Irrigated land – Availability of fertile soils + Irrigated land	–
Livestock production – Availability of rangelands + Livestock production	–

Although certain variables and ecological processes such as hydrogeological dynamics, biodiversity associated with land use, effects of fires and hurricanes on irrigated land, and soil salinization are important in the real system, they were not covered in our model. We ruled out these variables because they were not related directly or indirectly to the depopulation process for the study period.

According to this structure, we expected the growth of the population and economic activities to continue until their environmental constraints occurred. Thus, a basal emigration flow of population excess would occur. This expected behavior agreed with the real system dynamics for the 1900–1940 period, when the population reached its peak for the study period. However, some changes had to occur to reverse the dynamics to the observed decline. The analysis of the historical trends inside and outside the oasis of Comondú provided us with the answers.

Historical trends and reference mode of the main system variables

We divided the study period into four stages to more easily identify changes and possible drivers:

The Golden Age (1900–1940)

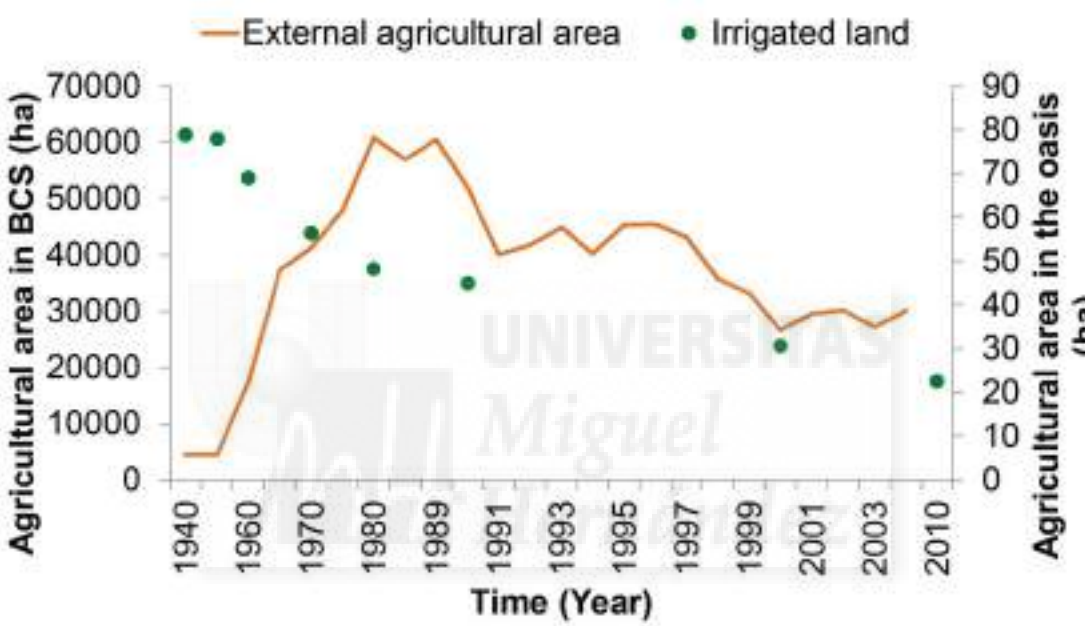
The traditional livelihood in the oasis of Comondú was based on irrigated agriculture, complemented by ranching. The entire area devoted to irrigated land was used for production (80 ha). We identified 92 orchards related to 75 producers, which had an average size of 1 ha (0.3–2.4 ha). Ranching was concentrated on the private lands in the surroundings (37,000 ha). We estimated an initial number of 38 occupied ranches in 20 private properties, which had an average size of 1840 ha (52–4900 ha). While irrigated land depended on the groundwater that emerged from several springs, ranching relied on rainfall supplies. The availability of water on irrigated land did not change during the historical period, not even in times of drought. The maximum flow was 72.66 liters per second (see more about the water flows and quality in Wurl *et al*. 2013, Gámez *et al*. 2014). The main agricultural products were date palms, sugar cane, grapes, figs, olives, other fruit trees, cereals, and vegetables (see more about the agrobiodiversity in de Grenade and Nabhan 2013). We estimated the average agricultural production was about 2.7 tons per hectare. Livestock activity was based mainly on cattle. Traditionally and locally processed products included wine and sweets derived from sugar cane. Two local institutions for irrigation management ensured irrigation system functioning, including water distribution, infrastructure maintenance, monitoring tasks, and penalties for violations. In order to overcome difficulties from erratic rainfall, ranchers adopted some strategies: rotating grazing, selling surplus animals, and importing hay.

The oasis of Comondú played a central role in the economy and development of BCS. It was the municipality seat of Comondú. The oasis had numerous shops, professional skills (tailoring, blacksmithing, carpentry), and a good provision of public services (schools, medical clinic, post office, telegraph), and most commodities consumed and produced locally, while surpluses were exported to urban centers in the same state and to other parts of Mexico, such as Mazatlán and Guadalajara. This stage was characterized by a growth in the oasis' population, economy, and production, and a high degree of self-sufficiency. Although, it was a time with more social inequality, and there were nearly 1000 inhabitants, only 20 families owned most of the productive land.

The Fall of Traditional Livelihood (1940–1960)

In the late 1940s, Mexico was concerned about colonizing the territory of BCS to avoid a possible invasion from the United States (Romero 1983, Urciaga 2008). The first attempt was made in 1941, with the agricultural colony named "María Auxiliadora," which failed after 4 years. This agrarian colonization process was also supported by the policies implemented by Manuel Avila Camacho, President of Mexico for the 1940–1946 period. He undertook various commitments to help Mexico follow a path of economic growth that was consistent with that of the United States. One of these commitments was an agricultural research program, known worldwide as the "Green Revolution" (Perfecto *et al*. 2009). Since 1949, strong successful agricultural modernization, supported by groundwater pumping, has occurred (Fig. 7). The municipality seat of Comondú was transferred to the new agricultural valley of Santo Domingo, first named as "El Crucero," and as "Ciudad Constitución" after 1971.

Fig. 7. The external agricultural area in Baja California Sur (BCS) versus the irrigated land in the oasis of Comondú. The orange line indicates the external agriculture; green points denote irrigated land. Source: Urciaga (2008), in depth interviews, and GIS (fieldwork).



In the oasis of Comondú, agriculture on irrigated land was gradually abandoned (Fig. 7). The oasis changed from selling products to the valley of Santo Domingo to buying the products produced in the valley of Santo Domingo. The new capital of the municipality and the small cities in the state acted as poles that attracted the inhabitants of Comondú who sought educational and professional opportunities, and a new lifestyle.

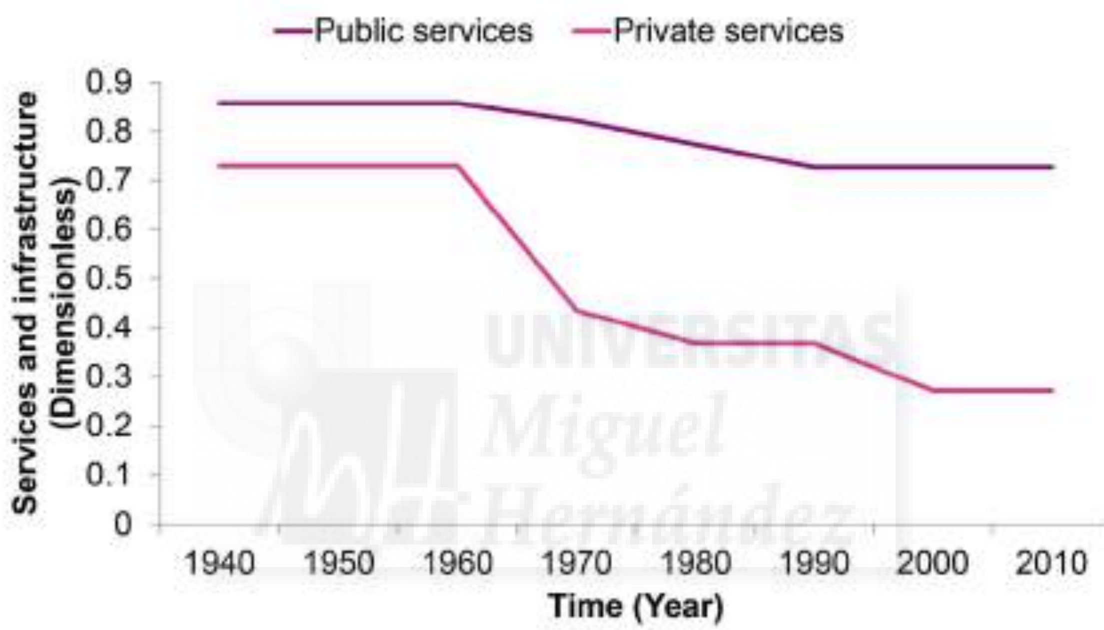
A New Hope (1960–1980)

The traditional agriculture of the oasis continued to decline in size and production terms, and suffered from poor access to distant markets. Local institutions for irrigation management collapsed.

The new Transpeninsular Highway, the most important road on the peninsula, bypassed the oasis and left it relatively isolated. Tourism was sponsored and developed by the federal government in coastal areas.

Comondú was essentially marginalized. Both public and private services declined (Fig. 8): i.e., public services like schools, post offices, and telegraphs, and private services like local shops, professional skills, community works, and local institutions.

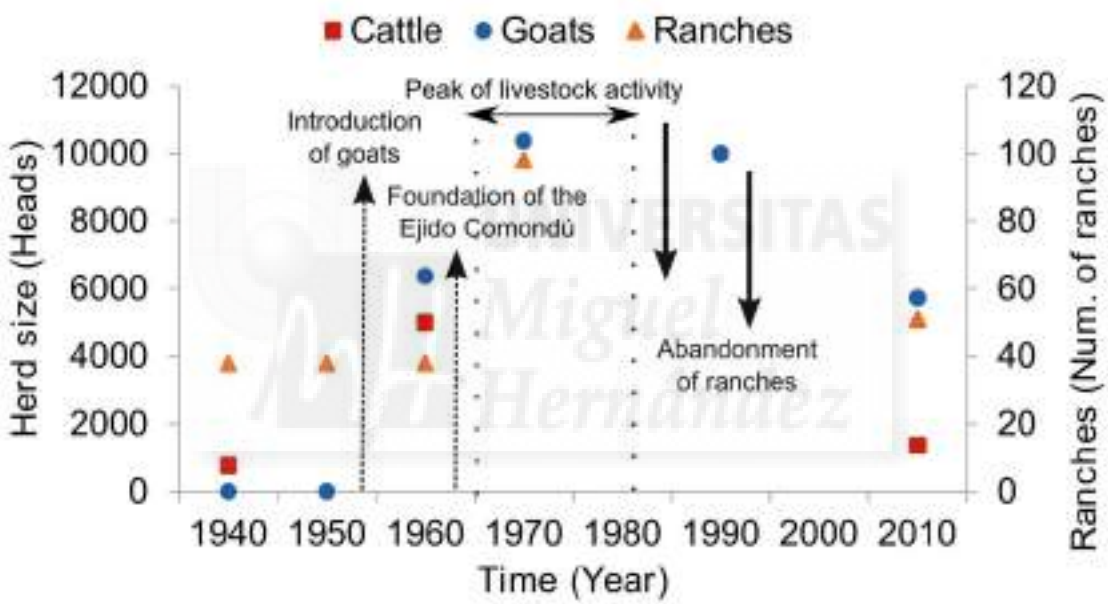
Fig. 8. Qualitative representation of the historical trend of public and private services. The violet line marks public services, including education, medical and religious services, post office, telegraphs, public telephone, electricity and water, transport, administration, and security. The pink line indicates private services, including local shops, professional skills, local institutions, community works, and local festivities. Source: indepth interviews.



Livestock activity became the main economic activity of the oasis, starting with cattle, and then with goats, which were introduced after the 1950s after goat herding had been successful in nearby oases. One of the keys to the goat herding success was the profit made from sales of young goats in October and January (we estimated the birth of one young goat per adult goat per year), and from the production of cheese every 2 weeks from October through May in wet years and from October to March in dry years. We estimated goat cheese production was about 21 kg per goat in wet years and 11 kg per goat in dry years. Goat products were marketed in other parts of Mexico, such as Monterrey, Nuevo León, and Sinaloa, through intermediary merchants. In 1968, the “Ejido Comondú” was created, which provided 70,000 ha of common lands to landless people (a list of 60 “ejidatarios” or ejido members was registered). This was a new local institution for managing rangeland and temporary water sources in a common pool resource in dry lands.

Between the 1970s and 1980s, ranching reached its peak production, and supported more than 10,000 goats and the largest number of families (about 100) that lived on ranches (Fig. 9). Each rancher could handle herds that averaged 133 goats and 100 cattle. The greater the size of the herd, the greater the labor needed.

Fig. 9. Livestock activity in the oasis of Comondú. Orange triangles denote occupied ranches, red squares are cattle, and blue points are goats. Dashed arrows indicate the introduction of goats and the creation of the Ejido Comondú; dotted lines indicate the period with the largest number of occupied ranches and heads of cattle and goats (1970–1980). The periods when ranches were abandoned are indicated with black arrows. Source: The 1962 General and Agricultural Census of the Official Gazette of the Government of the Territory of Baja California Sur (1968), and in-depth interviews.

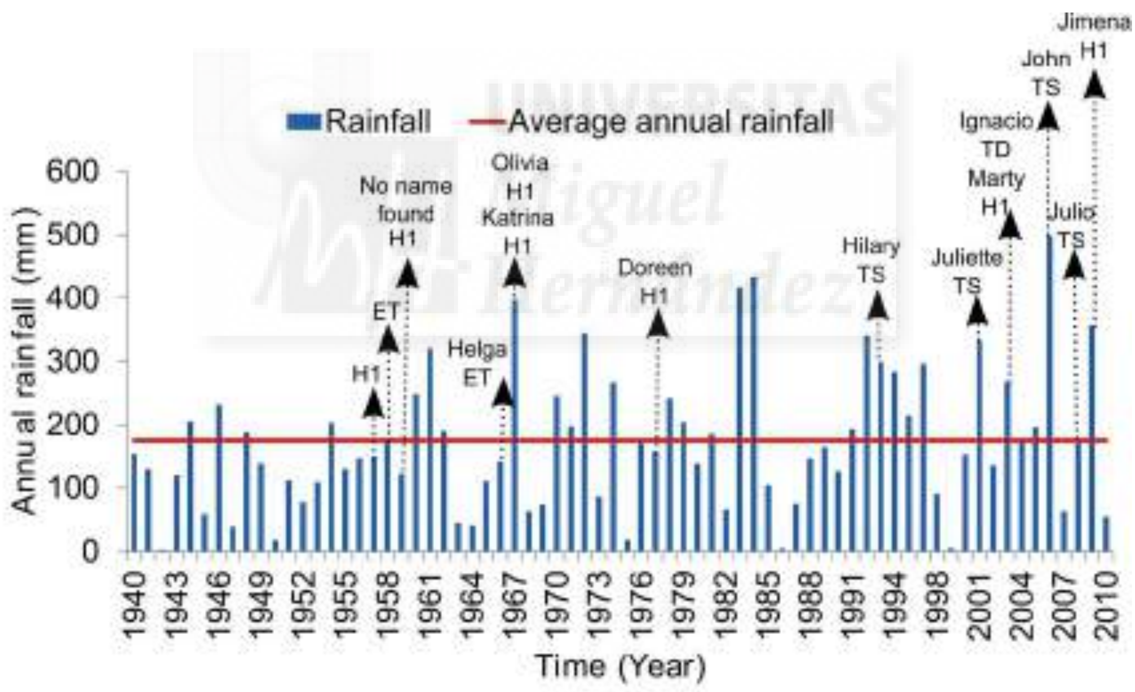


This stage was characterized by economic alleviation and a more equitable distribution of resources. With nearly 500 inhabitants, approximately 80 families owned productive lands (60 owners of common lands, and 20 owners of private lands).

The Age of Uncertainty (1980–2010)

As Fig. 10 shows, hurricanes and droughts have been frequent disturbances in the history of this system. There is no significant evidence for a change in the frequency and intensity of these events over time. Yet during this stage, the consequences of social weakening became more evident than ever. In addition, dependence on livestock activity destabilized the system dynamics once again. Despite the strategies previously mentioned (rotating grazing, selling surplus animals, and importing hay), droughts led to losses of up to 62% of goats and 40% of cattle in 1 year. Droughts also attracted large predators: coyotes, cougars, and bobcats. In 1 year, a rancher could lose 20% of their goats and 10% of their cows to predators. Diseases were also more common. Three hurricanes seriously affected livestock production in 2001, 2006, and 2009, and led to further losses of goats and cattle. Hurricane Jimena was the most intense, and ranchers claimed losses of 2–67% of their goats.

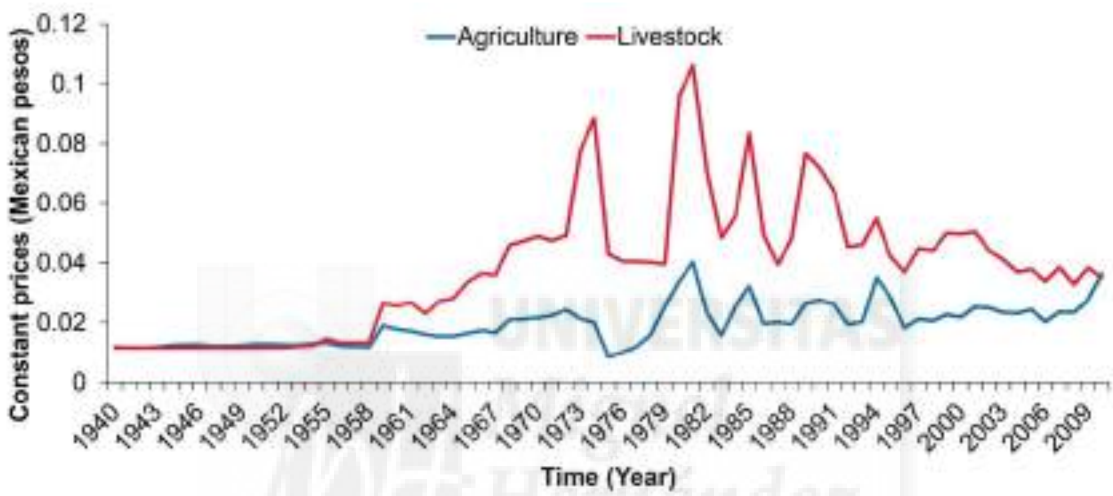
Fig. 10. Rainfall, droughts, and hurricanes. The years with rainfall that was less than the average annual rainfall rate are considered drought years. Hurricanes are indicated with dotted lines. The official register of hurricanes in Baja California Sur started in 1966. Hurricane wind categories are as follows: H5 (>135 knots), H4 (114–135 knots), H3 (96–113 knots), H2 (83–95 knots), H1 (64–82 knots), TS (tropical or subtropical storm; 34–63 knots), TD (tropical depression; < 34 knots), and ET (extra-tropical storm, varies). Source: Climatic data (1940–2010) from Weather Station 3008 (San José de Comondú) of the National Water Commission of Mexico, and Historical Hurricane Tracks from the National Oceanic and Atmospheric Administration (https://coast.noaa.gov/hurricanes/).



From 1986 to 2010, more than 50 families abandoned their ranches and emigrated because of devastating effects of hurricanes and droughts on livestock (Fig. 9). This coincided with a difficult period in Mexico's economy as the Mexican peso devaluated internationally, which was known as the "Tequila crisis," and it affected prices of commodities.

The regional market prices of the main products from the oasis have shown increased profitability for livestock products versus agricultural products since the middle of the 1950s. However, prices of livestock products reflected the greatest fluctuations (Fig. 11).

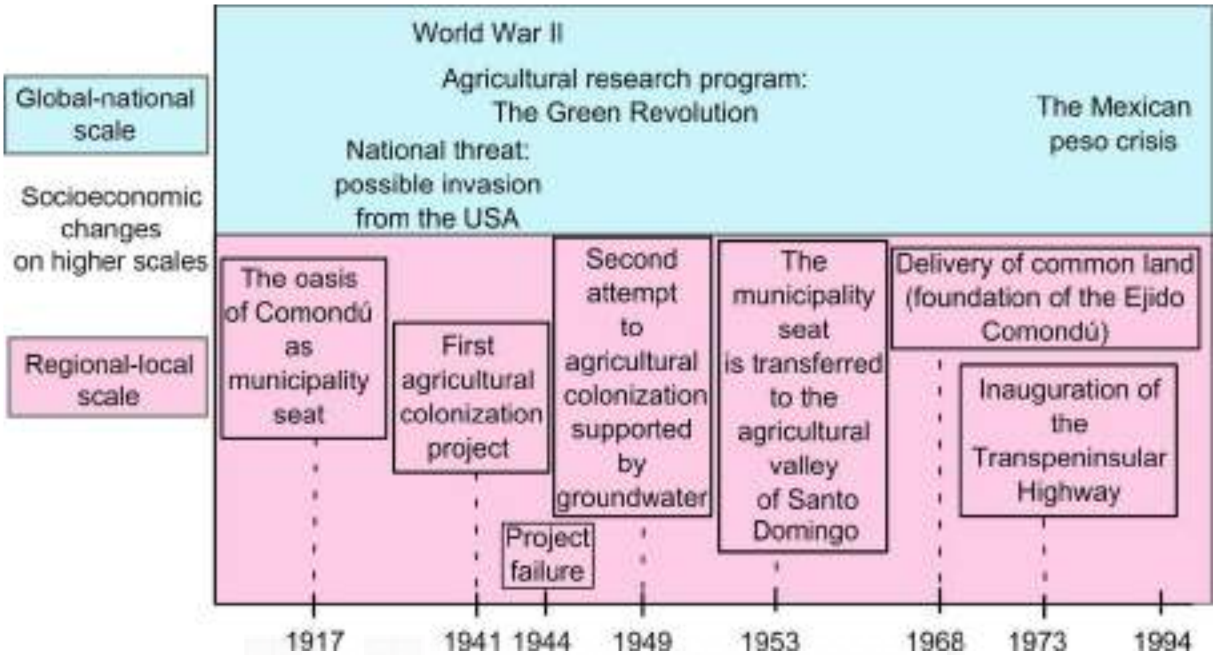
Fig. 11. Regional market prices of the main agricultural and livestock products of the oasis (constant prices with 1975 taken as the base year). The blue line represents the price of agricultural products (dates, sugar cane, and grapes), and the red line denotes the price of livestock products (cattle, goats, and goat's cheese). Source: 1929–1998: historical statistics of Baja California Sur (SEDESOL 2002a, b, 2003); 1940–1998: historical statistics of Mexico Vol.1 (INEGI 2009); 1980–2010: data from the Agricultural Information System Consultation (SIACON). (http://www.siap.gob.mx/optestadisticasiacon2012parcialsiacon-zip/)



In 2010, when we did most of the fieldwork, only 30% of irrigated lands were used for production (24 ha), and livestock numbers continued to decline from lack of rain. We estimated that only 51 ranches were occupied. The accumulation of plant remains in canals and plots led to three major wildfires in the oasis since 1980. With Hurricane Jimena, orchards were flooded, and production and some soils were lost. We were able to verify the presence of salt crusts in 12% of orchard soil. Instability, uncertainty, social deterioration, and weakening of adaptability characterized this last stage.

Fig. 12 summarizes the most relevant and severe socioeconomic and socio-political changes on higher scales during the historical period. The changes at the regional level heavily influenced the dynamics at the local scale, but some of these changes were a response of decisions and processes that happened much at higher scales. The agricultural development in BCS was related to the necessity to colonize the territory, and with the Green Revolution, a global process that characterized the post-World War II period. This timeline scheme helps show the interconnection between scales.

Fig. 12. Socioeconomic changes on higher scales. The changes on the global–national scale are located on the blue stripe; regional and local changes are on the violet stripe.



Social-ecological changes and effects on resilience

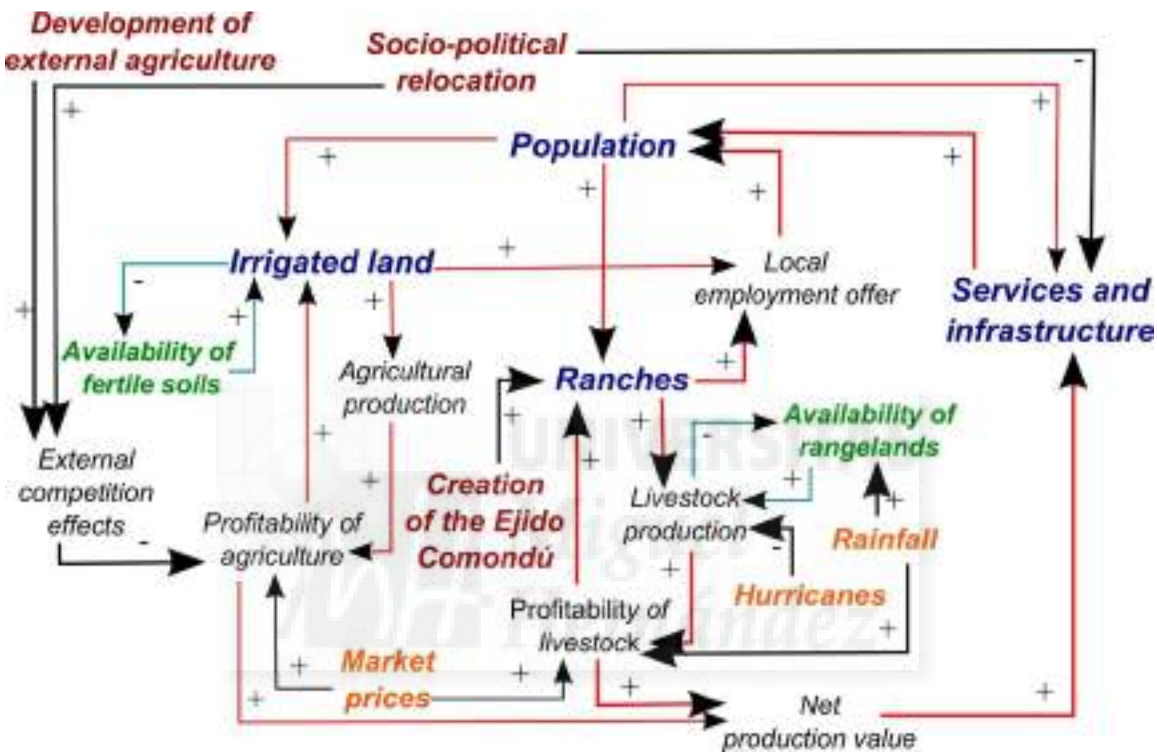
As shown in Fig. 6, the underlying structure of this system was dominated by positive feedback loops. Their tendency can be slowed down by specific limits to growth: availability of fertile soil and rangelands, in this case. However, the real system behavior indicated not only slowing growth but a reverse tendency to decline. Only the effect of external conditions or forcing functions could change the system behavior in this way. Into the causal loop diagram we integrated the main socioeconomic and sociopolitical changes in BCS during the study period (Fig. 13).

The profitability of agriculture suffered the effects of external competition, which has been defined by the development of external agriculture and socio-political relocation. Socio-political relocation represents the change in the municipality seat, the marginalization caused by the Transpeninsular Highway, and the deviation of public investment to other urban centers of BCS. Development of external agriculture represents the growth of modern and technician agriculture in the agricultural valleys of the state. This led to a displacement of the traditional production in the oasis to regional and national markets, which favored new export-oriented production.

Services were also affected by socio-political relocation because it meant less public investment in the oasis. The creation of the Ejido Comondú

implied the delivery of 70,000 ha of common land; this reinforced the rise in livestock activity.

Fig. 13. The causal diagram with the effects of new external conditions. These new external conditions are marked in red. In this case, the feedback loops associated with livestock activity are larger because they have a heavier relative weight in the system. The system's positive feedback loops were changed to red because it emphasizes the change in dynamics from growth to a reduction, and now they are vicious cycles.



implied the delivery of 70,000 ha of common land; this reinforced the rise in livestock activity. We identified two types of structural changes in the system: (1) the direction change in positive feedback loops from virtuous cycles to vicious cycles, and (2) a change in the relative weight of some variables and interactions.

Development of external agriculture and socio-political relocation reversed the direction of the positive feedback loops associated with agricultural activity and services in the oasis. The profitability drop caused irrigated land to decrease, which reduced the local employment offer and the economy of the oasis (net production value). The drop in public investment encouraged the disappearance of some public services and a deteriorated public infrastructure. The basal emigration flow was reinforced. The depopulation process weakened local institutions until they collapsed, and caused social disarticulation.

With agriculture declining, the resident population increased the relative weight of its ranching activity, firstly with cattle, and after the success in nearby oases, with goats. This change in the relative importance of productive activities was reinforced by the delivery of common lands, known as the creation of the Ejido Comondú.

Goat herding alleviated the economic situation of the oasis by increasing economy (net production value) and the local employment offer. However, cattle, and especially goats, are vulnerable to extreme weather events like droughts (which depend on rainfall) and hurricanes, which are relative frequent disturbances in the lifetime of the SES. Drought periods reduce the carrying capacity of rangelands and increase livestock mortality. Droughts also reduce the profitability of cattle due to imports of hay and other food supplements. Hurricanes provide the system with water, but also markedly increase livestock mortality. This means that the main economic activity of the oasis underwent significant fluctuations, which spread to the rest of the system, and the economy and local employment oscillated. These were unfavorable conditions for the population. Uncertainty and instability were factors that encouraged migration to other places that offered better conditions.

In relation to changes in SES resilience, in the first stage (“the Golden Age”) when the system was based on traditional agriculture, it was resilient to frequent disturbances like hurricanes and droughts. However, the system was not prepared for the slow persistent changes on higher scales represented by a set of political and economic changes. This caused traditional agriculture to decline and emigration to increase, both of which weakened the SES. The system adapted to new conditions by increasing the livestock activity role. Nevertheless, this change led to maladaptation because the SES became vulnerable to frequent disturbances, hurricanes, and droughts. The depopulation process continued, and the system is now unable to respond to new disturbances, and the ability to adapt to them is seriously limited.

In the SES of the oasis of Comondú, exogenous drivers are responsible for the endogenous changes that have led system dynamics to collapse. The depopulation process (an endogenous driver) was the effect of the slow, persistent changes on the higher scales but was also the cause of the deterioration and decline of this SES.

DISCUSSION AND GROUNDED SPECULATION

We have presented a qualitative model of a declining small-scale, long-lived SES, using the conceptualization process of the system dynamics approach. Our modeling approach has been useful for hypothesizing the structure of this SES, and for identifying the main drivers that triggered the dynamics toward collapse, deepening into the causal and feedback relationships, which other qualitative methods (e.g., adaptive cycles) do not perform well (Abel *et al*. 2006). As other authors have highlighted about the importance of the conceptualization process (Forrester 1992, Jørgensen and Bendoricchio 2001, Luna-Reyes and Andersen 2003), this modeling step permitted us to gather a rich set of qualitative and quantitative information that enables us to advance in the future modeling steps: quantitative modeling (including model evaluation), and exploration of future management scenarios. In addition, our methodological approach, especially the participant observation, has contributed to building a strong confidence relationship with local actors, which could support possible future participatory processes.

We qualitatively analyzed the structure and dynamics of the oasis of Comondú, a small-scale, long-lived SES, whose behavior has changed from well-functioning to decline. Analyzing the underlying structure of the system revealed that the system should grow until its environmental limits are reached, and then it should continue with relatively stable dynamics. However, the historical trends and data observed indicated a qualitative change in system dynamics. Only external drivers, changes on higher scales, could reverse the tendency from growth to reduction. The analysis of the effects of these changes on the system structure showed that performing external agriculture and a socio-politic relocation in BCS caused a severe depopulation process in the oasis. Likewise, this process dragged the entire system to display a tendency to collapse, which reversed the positive feedback loops from growth to reduction. The tendency of this SES to collapse was triggered by exogenous factors but was also maintained by the endogenous structure. The resilience of this SES suffered with these structural changes. One of these changes was to increase the relative weight of livestock activity in the economy of the oasis. This can be seen as an adaptation to the new external conditions, but it worsened the system's resilience and increased its vulnerability to extreme weather events. This situation is especially important because extreme weather events (i.e., hurricanes and droughts) might become more frequent due to climate change.

Despite the usefulness of qualitative models (Downing *et al*. 2014, Barber *et al*. 2015, Martone *et al*. 2017), we are aware of their limitations; thus, the results we have presented should be read cautiously. Our qualitative model does not include stocks and flows, and the deriving dynamic consequences from the causal loop diagram discussed could give us misleading conclusions (Vennix 1996). For this reason, the qualitative model constitutes only a hypothesis about the system structure. Building the quantitative dynamic simulation model is the necessary following step to test the hypothesis.

In any case, our results agree with not only the theories of collapse, where a drop in human capital could lead SESs to collapse (Motesharrei *et al*. 2014), but also with the theory of adaptive cycles, where collapse is preceded by loss of capital and loss of resilience (Holling 1987, 2001, Walker *et al*. 2006). Although the main drivers of collapse in our case study were exogenous, we considered that the inequity of resource distribution, especially land distribution, in the SES of the oasis of Comondú was a vulnerability cause that acted as a driving factor that increased the emigration flow when faced with new external conditions (Motesharrei *et al*. 2014). However, the scarcity of detailed land tenure data for the study period hindered the quantification of changes in land tenure over time.

The qualitative studies of SESs suggested that the effects of slow, persistent changes on higher scales (changes in socioeconomic conditions or technology) may lead to a relatively smooth transition of the SES, unlike top-down interventions (imposed changes of institutional arrangements) that hinder the SES' adaptations (Janssen *et al*. 2007). Our study suggests that the transition driven by effects of slow, persistent changes on higher scales could lead to a long-term SES maladaptation and could increase the vulnerability of the SES to frequent disturbances in the system.

Depopulation processes have undermined the traditional way of life in SESs and their local institutions because younger, healthier, and more educated people often migrate from communities (Reichert 1981, Stasiak 1992, Binford 2003, Collantes 2007). This selective migration involves loss of needed human and social capital from small-scale SESs when an endogenous approach to rural development is encouraged (Stockdale 2004). This is a critical point because rural development is necessary to revitalize and maintain these long-lived SESs, but they need human and social capital to achieve this.

In the SES of the oasis of Comondú, according to the roots of the depopulation problem, it seems that an improvement in the conditions and quality of life (local employment, services, economic growth, and stability) could convince migrant families to return or could attract new young people who are drawn to a different lifestyle. There is a worldwide countermovement of repopulation of rural small-scale, long-lived SESs (Buller and Hoggart 1994, Boyle and Halfacree 1998, Camarero *et al*. 2009), which has possibly been motivated or reinforced by the global financial crisis. The reorientation of regional policies to the oases of BCS (e.g., support for economic diversification, support to add value to local products, support to develop new market channels into organics, improve the provision of public services), and strengthening and restructuring the local communities of these oases (social networks, local institutions) could change current trends. However, we must identify and collect concrete policy measures and management options (suggested by local actors), and then integrate them into the dynamic simulation model to assess which combination of measures more efficiently reduces the depopulation process or even reverses it, among other possible management goals. In this way, the dynamic simulation model will be converted into a useful tool to more efficiently guide decision-making processes and the use of resources (Martínez-Fernández 2000, Pérez *et al*. 2012, Vidal-Legaz *et al*. 2013, Banos-González *et al*. 2016).

The results of this study and the development of the management model could serve as a methodological basis for other oases of the BCS or similar SESs, but in each case, modifications will be necessary to adapt the model to specific problems and local conditions (Jørgensen and Bendoricchio 2001).

The study of small-scale, long-lived SESs could assist in solving their specific problems in order to maintain them in their functional and desired states. Their conservation in the long-term could catalyze a transition in the way our society relates to the environment, reconciling the use of natural resources with biodiversity conservation and food security in a sustainable way. Long-lasting SESs are examples of more sustainable models of life compared to our globalized industrial society. They promote biodiversity, and possess a set of knowledge and practices that allow them to cope with perturbations and sustain yields without use of agrochemicals (Altieri 2009). They are not perfect, and they are suffering many changes. However, we can see them as a kind of "seeds" for a new global change. Hundreds of experiences in Latin America and Africa have shown how the traditional ecological knowledge of these SESs could be enriched by innovations and ecological principles to improve productiveness and the efficient use of labor and local resources (Altieri 1999, 2009). The collaboration and cooperation between local communities, NGOs, academics, governments, and citizens in general (as consumers) is necessary to encourage this transition. Successes in local experiences, and their reproduction could have an effect at the global scale.

CONCLUSIONS

We suggest the use of the system dynamics approach and building management models as a comprehensive and useful tool to address the specific problems of SESs, and assess alternative management options to solve them, avoiding panaceas. We present the first step, the conceptualization process, which provides a rich amount of information about the system under study, allows visualization of the system's hypothesized structure related to the observed behavior (deepening into the causal and feedback relationships), and establishes the basis for quantitative modeling. Our study about the oasis of Comondú (BCS, Mexico), a small-scale, long-lived SES that has lived a dramatic transition from well-functioning to decline in recent decades, agrees with collapse theories and adaptive cycles, and identifies a reduction in capital and resilience as signs of the tendency toward collapse. The slow, persistent changes (the development of external agriculture and a socio-politic relocation in BCS) caused a severe depopulation process in the oasis. This process dragged the entire system toward decline. This tendency was triggered by exogenous factors but was maintained by the endogenous structure. In our case study, the effects of slow, persistent changes led to a long-term SES maladaptation, which increased the vulnerability of the system to frequent disturbances (hurricanes and droughts). The conceptual model we presented has limitations because it does not include stocks and flows. Quantitative modeling is the necessary following step to test it. We expect to use the results of the entire research to analyze the system behavior, assess the effects of alternative management options, and support decision-making processes for improving local conditions and restoring the system's well-functioning.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/9176

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LITERATURE CITED

Abel, N., D. H. M. Cumming, and J. M. Anderies. 2006. Collapse and reorganization in social-ecological systems: questions, some ideas, and policy implications. *Ecology and Society* 11(1):17. http://dx.doi.org/10.5751/es-01593-110117

Anderies, J. M. 2000. On modeling human behavior and institutions in simple ecological economic systems. *Ecological Economics* 35:393–412. http://dx.doi.org/10.1016/S0921-8009(00)00221-4

Altieri, M. A. 1999. Applying agroecology to enhance the productivity of peasant farming systems in Latin America. *Environment, Development and Sustainability* 1:197–217. http://dx.doi.org/10.1023/A:1010078923050

Altieri, M. A. 2009. Agroecology, small farms, and food sovereignty. *Monthly Review* 61 (3):102–113. http://dx.doi.org/10.14452/mr-061-03-2009-07_8

Arriaga, L., and R. Rodríguez-Estrella. 1997. *Los Oasis de la Península de Baja California*. CIBNOR, La Paz, Mexico.

Banos-González, I., J. Martínez-Fernández, and M. A. Esteve-Selma. 2015. Dynamic integration of sustainability indicators in insular socio-ecological systems. *Ecological Modelling* 306:130–144. http://dx.doi.org/10.1016/j.ecolmodel.2014.08.014

Banos-González, I., J. Martínez-Fernández, and M. A. Esteve-Selma. 2016. Using dynamic sustainability indicators to assess environmental policy measures in biosphere reserves. *Ecological Indicators* 67:565–576. http://dx.doi.org/10.1016/j.ecolind.2016.03.021

Baral, N., M. J. Stern, and J. T. Heinen. 2010. Growth, collapse, and reorganization of the Annapurna Conservation Area, Nepal: an analysis of institutional resilience. *Ecology and Society* 15(3):10. http://dx.doi.org/10.5751/es-03534-150310

Barber, M., S. Jackson, J. Dambacher, and M. Finn. 2015. The persistence of subsistence: qualitative social-ecological modeling of indigenous aquatic hunting and gathering in tropical Australia. *Ecology and Society* 20(1):60. https://www.ecologyandsociety.org/vol20/iss1/art60/

Baur, I., and C. R. Binder. 2015. Modeling and assessing scenarios of common property pastures management in Switzerland. *Ecological Economics* 119:292–305. http://dx.doi.org/10.1016/j.ecolecon.2015.09.019

Becker, H., and B. Geer. 1957. Participant observation and interviewing: a comparison. *Human Organization* 16:28–32. http://dx.doi.org/10.17730/humo.16.3.k687822132323013

Bert, F. E., G. P. Podestá, S. L. Rovere, A. N. Menéndez, M. North, E. Tatara, C. E. Laciana, E. Weber, and F. R. Toranzo. 2011. An agent based model to simulate structural and land use changes in agricultural systems of the Argentine pampas. *Ecological Modelling* 222:3486–3499. http://dx.doi.org/10.1016/j.ecolmodel.2011.08.007

Binford, L. 2003. Migrant remittances and (under) development in Mexico. *Critique of Anthropology* 23:305–336. http://dx.doi.org/10.1177/0308275X030233004

Boyle, P., and K. Halfacree. 1998. *Migration into rural areas*. Wiley and Sons, Chichester, United Kingdom.

Brander, J. A., and M. S. Taylor. 1998. The simple economics of Easter Island: a Ricardo-Malthus model of renewable resource use. *American Economic Review* 88(1):119–138.

Bueno, N., and X. Basurto. 2009. Resilience and collapse of artisanal fisheries: a system dynamics analysis of a shellfish fishery in the Gulf of California, Mexico. *Sustainability Science* 4:139–149. http://dx.doi.org/10.1007/s11625-009-0087-z

Buller, H., and K. Hoggart. 1994. *International counterurbanization: British migrants in rural France*. Aldershot, Avebury, UK.

Camarero, L., F. Cruz, M. González, J. A. del Pino, J. Oliva, and R. Sampedro. 2009. *La población rural de España. De los desequilibrios a la sostenibilidad social*. Fundación La Caixa, Barcelona, Spain.

Cariño, M. 2001. La oasisidad, núcleo de la cultura sudcaliforniana. *Gaceta Ecológica* 60:57–69.

Cariño, M., A. Breceda, A. Ortega, and L. Castorena, editors. 2013. *Evocando el edén. Conocimiento, valoración y problemática del Oasis de Los Comondú*. Icaria editorial S. A., Barcelona, Spain.

Cariño, M., and A. Ortega, editors. 2014. *Oasis sudcalifornianos. Para un rescate de la sustentabilidad local*. Editorial Universidad de Granada, Granada, Spain.

Cocks, K. D. 2003. *Deep futures: our prospects for survival*. University of New South Wales Press, Sydney, Australia.

Collantes, F. 2007. The decline of agrarian societies in the European countryside: a case study of Spain in the twentieth century. *Agricultural History* 81:76–97. http://dx.doi.org/10.3098/ah.2007.81.1.76

Costanza, R., and M. Ruth. 1998. Using dynamic modeling to scope environmental problems and build consensus. *Environmental Management* 22:183–195. http://dx.doi.org/10.1007/s002679900095

Coyle, G. 2000. Qualitative and quantitative modelling in system dynamics: some research questions. *System Dynamics Review* 16:225–244. http://dx.doi.org/10.1002/1099-1727(200023)16:3<225::AID-SDR195>3.0.CO;2-D

Dale, V. H., R. V. O'Neill, M. Pedlowski, and F. Southworth. 1993. Causes and effects of land-use change in central Rondonia, Brazil. Photogrammetric *Engineering & Remote Sensing* 59:997–1005.

de Grenade, R. , and G. P. Nabhan. 2013. Baja California peninsula oases: an agro-biodiversity of isolation and integration. *Applied Geography* 41:24–35. http://dx.doi.org/10.1016/j.apgeog.2013.03.008

Downing, A. S., E. H. van Nes , J. S. Balirwa, J. Beuving, P. O. J. Bwathondi, L. J. Chapman , I. J. M. Cornelissen, I. G. Cowx, K. P. C. Goudswaard, R. E. Hecky, J. H. Janse, A. B. G. Janssen, L. Kaufman, M. A. Kishe-Machumu, J. Kolding, W. Ligtvoet, D. Mbabazi, M. Medard, O. C. Mkumbo, E. Mlaponi, A. T. Munyaho, L. A. J. Nagelkerke, R. Ogutu-Ohwayo, W. O. Ojwang, H. K. Peter, D. E. Schindler , O. Seehausen, D. Sharpe, G. M. Silsbe, L. Sitoki , R. Tumwebaze, D. Tweddle, K. E. van de Wolfshaar, H. van Dijk, E. van Donk , J. C. van Rijssel, P. A. M. van Zwieten, J. Wanink, F. Witte, and W. M. Mooij. 2014. Coupled human and natural system dynamics as key to the sustainability of Lake Victoria's ecosystem services. *Ecology and Society* 19 (4):31. http://dx.doi.org/10.5751/ES-06965-190431

Duffy, S. B., M. S. Corson, and W. E. Grant. 2001. Simulating land-use decisions in the La Amistad Biosphere Reserve buffer zone in Costa Rica and Panama. *Ecological Modelling* 140:9–29. http://dx.doi.org/10.1016/S0304-3800(01)00266-6

Evans, T. P., A. Manire, F. de Castro, E. Brondizio, and S. McCracken. 2001. A dynamic model of household decision-making and parcel level landcover change in the eastern Amazon. *Ecological Modelling* 143:95–113. http://dx.doi.org/10.1016/S0304-3800(01)00357-X

Food and Agriculture Organization of the United Nations (FAO). 2014. *The state of food and agriculture: innovation in family farming*. FAO, Rome, Italy.

Forrester, J. W. 1958. Industrial dynamics: a major breakthrough for decision makers. *Harvard Business Review* 36:37–66.

Forrester, J. W. 1961. *Industrial dynamics*. Pegasus Communications, Waltham, Massachusetts, USA.

Forrester, J. W. 1969. *Urban dynamics*. Pegasus Communications, Waltham, Massachusetts, USA.

Forrester, J. W. 1973. *World dynamics*. Pegasus Communications, Waltham, Massachusetts, USA.

Forrester, J. W. 1992. Policies, decisions and information sources for modeling. *European Journal of Operational Research* 59:42–63. http://dx.doi.org/10.1016/0377-2217(92)90006-U

Forrester, J. W., and P. Senge. 1980. Tests for building confidence in system dynamics models. *TIMS Studies in the Management Sciences* 14:209–228.

Gámez, A. E., J. Wurl, and J. C. Graciano. 2014. Disponibilidad y uso del agua en el oasis de los Comondú, Baja California Sur: retos y oportunidades para el desarrollo rural. *Región y sociedad* 60:165–190.

Happe, K. 2005. Agent-based modeling and sensitivity analysis by experimental design and metamodelling: an application to modeling regional structural change. In: *XIth International Congress of the European Association of Agricultural Economists, the Future of Rural Europe in the Global Agri-Food System*. Copenhagen, Denmark.

Holling, C. S. 1987. Simplifying the complex: the paradigms of ecological function and structure. *European Journal of Operational Research* 30:139–146. http://dx.doi.org/10.1016/0377-2217(87)90091-9

Holling, C. S. 2001. Understanding the complexity of economic, ecological, and social systems. *Ecosystems* 4:390–405. http://dx.doi.org/10.1007/s10021-001-0101-5

Instituto Nacional de Estadistica y Geografia (INEGI). 2009. Estadísticas Históricas de México. Vol. 1. Tomo II. Tema 17, precios, México City, México.

Instituto Nacional de Estadistica y Geografia (INEGI). 2011. Marco Geoestadístico Nacional: Localidades geoestadísticas, archivo histórico. [online] URL:
http://www.inegi.org.mx/geo/contenidos/geoestadistica/introduccion.aspx

Janssen, M. A., J. M. Anderies, and E. Ostrom. 2007. Robustness of social ecological systems to spatial and temporal variability. *Society & Natural Resources* 20:307–322. http://dx.doi.org/10.1080/08941920601161320

Jørgensen, S. E., and G. Bendoricchio. 2001. *Fundamentals of ecological modelling*. Elsevier Science, Oxford, USA.

Lacitignola, D., I. Petrosillo, M. Cataldi, and G. Zurlini. 2007. Modelling socio-ecological tourism-based systems for sustainability. *Ecological Modelling* 206:191–204. http://dx.doi.org/10.1016/j.ecolmodel.2007.03.034

Li, F. J., S. C. Dong, and F. Li. 2012. A system dynamics model for analyzing the eco-agriculture system with policy recommendations. *Ecological Modelling* 227:34–45. http://dx.doi.org/10.1016/j.ecolmodel.2011.12.005

Luna-Reyes, L. F., and D. L. Andersen. 2003. Collecting and analyzing qualitative data for system dynamics: methods and models. *System Dynamics Review* 19:271–296. http://dx.doi.org/10.1002/sdr.280

Marín, V. H., L. C. Rodríguez, and H. M. Niemeyer. 2012. A socio-ecological model of the Opuntia scrublands in the Peruvian Andes. *Ecological Modelling* 227:136–146. http://dx.doi.org/10.1016/j.ecolmodel.2011.12.010

Martínez-Fernández, J., M. A. Esteve-Selma, I. Baños-González, F. Carreño, and A. Moreno. 2013. Sustainability of Mediterranean irrigated agro-landscapes. *Ecological Modelling* 248:11–19.
http://dx.doi.org/10.1016/j.ecolmodel.2012.09.018

Martínez-Fernández, J., M. A. Esteve-Selma, and J. F. Calvo-Sendín. 2000. Environmental and socioeconomic interactions in the evolution of traditional irrigated lands: a dynamic system model. *Human Ecology* 28:279–299. http://dx.doi.org/10.1023/A:1007024204961

Martone, R. G., A. Bodini, and F. Micheli. 2017. Identifying potential consequences of natural perturbations and management decisions on a coastal fishery social-ecological system using qualitative loop analysis. *Ecology and Society* (22)1:34. https://www.ecologyandsociety.org/vol22/iss1/art34/

Meadows, D. L., W. W. Behrens III, D. H. Meadows, R. F. Naill, J. Randers, and E. K. O. Zahn. 1974. *Dynamics of growth in a finite world*. Wright-Allen Press, Cambridge, Massachusetts, USA.

Meadows, D. H., D. L. Meadows, J. Randers, and W. W. Behrens III. 1972. *The limits to growth*. Universe Books, New York, USA.

Motesharrei, S., J. Rivas, and E. Kalnay. 2014. Human and nature dynamics (HANDY): modeling inequality and use of resources in the collapse or sustainability of societies. *Ecological Economics* 101:90–102. http://dx.doi.org/10.1016/j.ecolecon.2014.02.014

Musacchio, L. R., and W. E. Grant. 2002. Agricultural production and wetland habitat quality in a coastal prairie ecosystem: simulated effects of alternative resource policies on land-use decisions. *Ecological Modelling* 150:23–43. http://dx.doi.org/10.1016/S0304-3800(01)00459-8

Ostrom, E., M. A. Janssen, and J. M. Anderies. 2007. Going beyond panaceas. *Proceedings of the National Academy of Sciences of the United States of America* 104:15176–15178. http://dx.doi.org/10.1073/pnas.0701886104

Pérez, I., A. Tenza, J. D. Anadón, J. Martínez-Fernández, A. Pedreño, and A. Giménez. 2012. Exurban sprawl increases the extinction probability of a threatened tortoise due to pet collections. *Ecological Modelling* 245:19–30. http://dx.doi.org/10.1016/j.ecolmodel.2012.03.016

Perfecto, I., J. Vandermeer, and A. Wright. 2009. *Nature's matrix: linking agriculture, conservation and food sovereignty*. Earthscan, London, United Kingdom.

Portela, R., and I. Rademacher. 2001. A dynamic model of patterns of deforestation and their effect on the ability of the Brazilian Amazonia to provide ecosystem services. *Ecological Modelling* 143:115–146. http://dx.doi.org/10.1016/S0304-3800(01)00359-3

Randers, J. 1980. Guidelines for model conceptualization. Pages 117–139 in J. Randers, editor. *Elements of the system dynamics method*. MIT Press, Cambridge, Massachusetts, USA.

Reichert, J. S. 1981. The migrant syndrome: seasonal U.S. wage labor and rural development in Central Mexico. *Human Organization* 40:56–66. http://dx.doi.org/10.17730/humo.40.1.c6148p5743512768

Richardson, G. P., and A. L. Pugh, III. 1981. *Introduction to system dynamics modeling with DYNAMO*. Productivity Press, Cambridge, Massachusetts, USA.

Roberts, N., D. F. Andersen, R. M. Deal, M. S. Garet, and W. A. Shaffer. 1983. *Introduction to computer simulation: a systems dynamics approach*. Addison-Wesley, Boston, Massachusetts, USA.

Romero, R. 1983. *Baja California histórica y legendaria*. Costa-AMIC, Mexico City, Mexico.

Sanga, G. J., and E. D. Mungatana. 2016. Integrating ecology and economics in understanding responses in securing land-use externalities internalization in water catchments. *Ecological Economics* 121:28–39. http://dx.doi.org/10.1016/j.ecolecon.2015.11.011

Saysel, A. K., T. Barlas, and O. Yenigün. 2002. Environmental sustainability in an agricultural development project: a systems dynamics approach. *Journal of Environmental Management* 64:247–260. http://dx.doi.org/10.1006/jema.2001.0488

SEDESOL. 2002a. Estadísticas Históricas 1929–1956. Territorio Sur de Baja California. La Paz, Mexico: Gobierno del Estado de Baja California Sur.

SEDESOL. 2002b. Estadísticas Históricas 1956–1975. Territorio Sur de Baja California. La Paz, Mexico: Gobierno del Estado de Baja California Sur.

SEDESOL. 2003. Estadísticas Históricas 1975–1998. Estado de Baja California Sur. La Paz, Mexico: Gobierno del Estado de Baja California Sur.

Solecki, W. D., and C. Oliveri. 2004. Downscaling climate change scenarios in an urban land use change model. *Journal of Environmental Management* 72:105–115. http://dx.doi.org/10.1016/j.jenvman.2004.03.014

Stasiak, A. 1992. Problems of depopulation of rural areas in Poland after 1950. *Landscape and Urban Planning* 22:161–175. http://dx.doi.org/10.1016/0169-2046(92)90020-Z

Sterman, J. D. 2000. *Business dynamics: systems thinking and modeling for a complex world*. Irwin/McGraw-Hill, Boston, Massachusetts, USA.

Stockdale, A. 2004. Rural out-migration: community consequences and individual migrant experiences. *Sociologia Ruralis* 44:167–194. http://dx.doi.org/10.1111/j.1467-9523.2004.00269.x

Tenza, A., I. Pérez-Ibarra, J. Martínez-Fernández, F. J. Conway, M. Cariño, L. Castorena, A. Breceda, and A. Giménez. 2013. Estructura y funcionamiento dinámico del oasis. Pages 33–57 in M. Cariño, A. Breceda, A. Ortega, and L. Castorena, editors. *Evocando el edén. Conocimiento, valoración y problemática del Oasis de Los Comondú*. Icaria editorial S. A., Barcelona, Spain.

Tomlinson, B., S. Sastre, D. Blasco, and J. Guillén. 2011. The systems approach framework as a complementary methodology of adaptive management: a case study in the urban beaches of Barcelona. *Ecology and Society* 16(4):28. http://dx.doi.org/10.5751/es-04484-160428

Turchin, P., and S. A. Nefedov. 2009. *Secular cycles*. Princeton University Press, Princeton, New Jersey, USA. http://dx.doi.org/10.1515/9781400830688

Turner, B. L., V. Tidwell, A. Fernald, J. A. Rivera, S. Rodriguez, S. Guldan, C. Ochoa, B. Hurd, K. Boykin, and A. Cibils. 2016. Modeling Acequia irrigation systems using system dynamics: model development, evaluation, and sensitivity analyses to investigate effects of socio-economic and biophysical feedbacks. *Sustainability* 8(10):1019. http://dx.doi.org/10.3390/su8101019

Urciaga, J. 2008. La agricultura en Baja California Sur. Una perspectiva de largo plazo (1900–2005). Pages 249–278 in M. Cariño and M. Monteforte, editors. *Del saqueo a la conservación. Historia ambiental contemporánea de Baja California Sur, 1940–2003.* UABCS, SEMARNAT, INE, and CONACYT, Mexico City, Mexico.

Urgenson, L. S., R. K. Hagmann, A. C. Henck, S. Harrell, T. M. Hinckley, S. J. Shepler, B. L. Grub, and P. M. Chi. 2010. Socialecological resilience of a Nuosu community-linked watershed, southwest Sichuan, China. *Ecology and Society* 15(4):2. http://dx.doi.org/10.5751/es-03568-150402

Vang Rasmussen, L., and A. Reenberg. 2012. Collapse and recovery in Sahelian agro-pastoral systems: rethinking trajectories of change. *Ecology and Society* 17(1):14. http://dx.doi.org/10.5751/es-04614-170114

Vennix, J. A. M. 1996. *Group model building. facilitating team learning using system dynamics*. John Wiley & Sons, Chichester, UK.

Vidal-Legaz, B., J. Martínez-Fernández, A. Sánchez-Picón, and F. I. Pugnaire. 2013. Trade-offs between maintenance of ecosystem services and socio-economic development in rural mountainous communities in southern Spain: a dynamic simulation approach. *Journal of Environmental Management* 131:280–297. http://dx.doi.org/10.1016/j.jenvman.2013.09.036

Walker, B., L. Gunderson, A. Kinzig, C. Folke, S. Carpenter, and L. Schultz. 2006. A handful of heuristics and some propositions for understanding resilience in social-ecological systems. *Ecology and Society* 11(1):13. http://dx.doi.org/10.5751/es-01530-110113

Wolstenholme, E. 1990. *System enquiry: a system dynamics approach*. John Wiley & Sons, New York, USA.

Wurl, J., J. C. Graciano, and A. E. Gámez. 2013. Disponibilidad, calidad y manejo del agua para su uso productivo y humano en Los Comondú. Pages 149–177 in A. E. Gámez, editor. *Opciones de desarrollo en el oasis de Los Comondú*. La Paz, Mexico: Gobierno del Estado de Baja California Sur, Instituto Sudcaliforniano de Cultura, Universidad Autónoma de Baja California Sur, Consejo Nacional de Ciencia y Tecnología.

Xiao-Qing, Z., R. Hui, Y. Qi, H. Chun-lan, and Y. Hong-hui. 2012. Scenarios simulation on carrying capacity of water resources in Kunming City. *Procedia Earth and Planetary Science* 5:107–112. http://dx.doi.org/10.1016/j.proeps.2012.01.018

Young, O. R., F. Berkhout, G. C. Gallopin, M. A. Janssen, E. Ostrom, and S. van der Leeuw. 2006. The globalization of socioecological systems: an agenda for scientific research. *Global Environmental Change* 16:304–316. http://dx.doi.org/10.1016/j.gloenvcha.2006.03.004

Appendix 1. List of RIDISOS researcher members.

Name	Discipline	Academic institution
Alba. E Gámez	Economy	Universidad Autónoma de Baja California Sur, Mexico
Alexandra Sauvage	Cultural history	Universidad Autónoma de Baja California Sur, Mexico
Alicia Tenza	Environmental sciences and Agroecology	Universidad Miguel Hernández, Spain
Andrés Giménez	Ecology	Universidad Miguel Hernández, Spain
Antonina Ivanova	Economy	Universidad Autónoma de Baja California Sur, Mexico
Antonio Ortega	Environmental history	Universidad de Granada, Spain
Aurora Breceda	Ecology	Centro de Investigaciones Biológicas del Noroeste (CIBNOR), Mexico
Eduardo Juárez	Economy	Universidad Autónoma de Baja California Sur, Mexico
Frederick J. Conway	Anthropology	University of San Diego, United States of America
Irene Pérez	Ecology and Sociology	Arizona State University, United States of America
Jobst Wurl	Hydrogeology	Universidad Autónoma de Baja California Sur, Mexico
José A. Martínez de la Torre	Economy	Universidad Autónoma de Baja California Sur, Mexico
Julia Martínez	Ecology	Fundación Nueva Cultura del Agua, Spain
Lorella Castorena	Sociology	Universidad Autónoma de Baja California Sur, Mexico
Mario Monteforte	Marine Biology	Centro de Investigaciones Biológicas del Noroeste (CIBNOR), Mexico
Micheline Cariño	Environmental history	Universidad Autónoma de Baja California Sur, Mexico
Paul Nabhan	Ecology and Ethnobotany	Universersty of Arizona, United States of America
Rafael de Grenade	Cultural anthropology and Agricultural Plant Science	University of Arizona, United States of America
Yolanda Maya	Edaphology	Centro de Investigaciones Biológicas del Noroeste (CIBNOR), Mexico

Appendix 2. Interview scripts.

General Interview: irrigation, land tenure and community (population and services)

(conducted between November-December 2010)

Block 1. Characterization of the interviewee

What is your name?
How old are you?
Were you born in this community?
Have you always lived here? If not ... Where? For how long? Why did you come back?
Were your parents from here?
In what productive activity are you engaged?

Block 2. Characterization of the orchard

Do you have an orchard in this community? Are you the owner of the orchard or are you in charge?
How large is your orchard?
Is your orchard currently in production? What do you produce? How much do you produce in a year (or a season)? How long have you been working on this orchard?
How long have you been engaged in agricultural activity?
What activities do orchard maintenance and production include?
Has the orchard always been in production or has it been inactive during a prior period? If it has been inactive, when? For how many years?
What did you grow before? If you changed, why did you change the crop type?

Block 3. Characterization of the agricultural activity in the community

Do you remember seeing all the orchards in production? When?
Could you tell me about the maximum area that has been in production?
What is the average area of the orchards? What is the maximum and minimum area?
What are the main crops of the community? Have they changed with time? Why?
How much could be produced on a plot of dates, figs, grapes or sugar cane in a year?

Some of the orchards that we visited have been abandoned for 30 and 40 years. Do you know of any cases where someone has recovered an abandoned orchard? Why?
When were orchards larger? How many? Who were the owners? What happened to the people who did not own orchards?
What is the traditional land inheritance system in the oasis?

Block 4. Marketing and profitability of agricultural activity

Has there been any association or cooperative that has marketed agricultural production?
How was the product marketed in the past? And now?
Where were orchard products sold? And now?
Does the community use inputs (pesticides, fertilizers, etc.) for the orchards?
Was livestock farming performed at the same time as the orchards?
Is the agricultural activity complemented by livestock? Has it sold manure as a fertilizer to neighbors?
Why do you think the agricultural activity stopped being profitable?
To what extent do you think that the opening of the Santo Domingo Valley has affected production of the oasis?
When did the population engage more time in livestock activity than in agriculture? Is it more profitable?
When were goats introduced into Comondú? Did it form part of some government support?
What are the main reasons for abandoning orchards?

Block 5. Irrigation

What kind of irrigation was used on the orchards in the past?
Did any local institution regulate the irrigation of orchards? How did it work?
What was irrigation system cleaning and maintenance like? And now?
When did the institution for irrigation stop working?
What was the reason for the disruption?
What is irrigation like now?

Block 6. Land tenure

Are you an ejidatario or a private owner?
What properties do you have (housing, orchard, ranch)? What is the property type for each one?
When was the Ejido created?
Did all families have the opportunity to form part of the Ejido?
Did the creation of the Ejido affect orchards being abandoned?

Block 7. Characterization of the community

Has the number of neighbors varied with time? Could you estimate the maximum number of neighbors who have lived here in relation to a specific date?
What services did the community have before (schools, shops, post office, telegraphs, etc.)?
What year did each one cease being active?
From your point of view, which of the services you mentioned was the most important? And the least?
Were there festivities or dances in the community? How often? When did they stop being held?
Do you remember any period during which a larger number of residents migrated to other parts? When?
What were the main reasons for this migration?

General interview: ranches

(Conducted in January 2011)

Block 1. Characterization of the interviewee

Name:
Age:
Name of community:
How many years have you worked with livestock?

Block 2. Characterization of the ranch

What is the name of your ranch?
Are you the owner of the ranch or you are a worker?
What type of property is the ranch?
Have you always lived in the area? How long have you worked at or have you owned the ranch?
What surface area does your ranch cover?
How much area is used for cattle? And for goats?

Block 3. Characterization of livestock activity

How many heads of cattle do you currently have? and goats?
What is the largest number of cattle and goats that you have had? When was this?
And the fewest? When was this?

How long have you had goats?
What factors determine changes in livestock with time?
What are the reasons for you not having more cattle (ranch size, economic reasons)?
Where do your livestock graze on?
Do you change grazing areas throughout the year or between years? Why? How?
Are there mechanisms for rangeland management? Are there rules for rangeland regeneration?

Block 4. Production and profitability of livestock activity

How many people work on the ranch? Are they a family?
What production figures does your ranch yield? How has it changed with time?
How do you market the production of your ranch? How has it changed with time?
What are the production costs of your ranch? How have they changed over time?
Are there any differences between costs of goats and cattle?
What is the profitability of livestock? How has it changed with time?
Are there any differences between the profitability of cattle and goats? If so, what are they?
What is the self-consumption production?
How many people depend on the resources obtained from your ranch?

Block 5. Effects of weather

Do you remember years with heavy rain? When? How does rain affect the ranch (grass, livestock, production)?
And drought periods? When? How does drought affect the ranch (grass, livestock, production)?
Have you experienced events like hurricanes? Do you remember any specific hurricane? When did it occur? How did it affect the ranch? How much livestock loss occurred in these events?
What do you do to adapt to extreme weather events?

Block 6. Relations with the community and other ranches

How do you relate to the community? How often do you visit the community? What are the main reasons for going to the community?
How are rangeland areas shared among neighboring ranches?
Is there any conflict?

Block 7. Perceived problems in livestock activity and future perspectives

What problems does livestock activity entail now?
Have any ranches been abandoned? Since when? How much? Where?
Do generational replacements take place to work in livestock activity?
How do you see the future of ranching? Do you want to continue with it? What about your children?
What could improve the current situation of ranches?

Specific interview: migrants

(Conducted in February 2012)

What is your name?
How old are you?
Where were you born?
How many years have you lived in the oasis of Comondú?
How old were you when you left the oasis of Comondú?
How would you describe the life in the oasis when you lived there (neighbors, economic activities, services, festivities, etc.)?
What reasons helped you make the decision to migrate from the Oasis Comondú (educational opportunities, work, health, quality of life, etc.)?
Did some friend, neighbor or family member (who had migrated before) help you to make the decision?
Did you need financial support to migrate from the oasis? Did this support come from your family? What main economic activities did your family undertake in the oasis of Comondú?

Specific interview: livestock activity

(Conducted in August 2012)

How many goats or cattle are necessary to start a herd?
How many years do goats live? And cattle? How many years can goats breed? And cattle?
What are livestock activity costs? (Labor, fuel, etc.)
How many people are needed to manage a ranch? How many cattle or goats can one single person handle?
What costs increase with drought?
What happens to prices? Can you offset costs? How many differences are there between the profits and costs of livestock during drought periods?

Imagine a herd of 100 goats or cattle, and a dry year begins ... What would happen to that herd? How many goats or cattle would die? Would you sell all goatlings or calves (females and males) in that year? What would happen if the drought lasted another year? and 2 years?
Does a dry year have any effects on rangelands?
What factors (profitability, duration of droughts, herd size) could affect making a decision about abandoning livestock activity? Which of these factors has more weight?
What is done with the animals when a rancher decides to leave a ranch?

Appendix 3. Summary of quantitative data from fieldwork.

Parameter	**Value**	**Units**
Abandonment rate of irrigated land (reference value)	0.0025	1/year
Animal units per cattle (used to calculate the carrying capacity of rangeland)	1	AU/cattle
Animal units per goat (used to calculate the carrying capacity of rangeland)	0.17	AU/goat
Average rainfall (1940-2010)	175	mm/Year
Birth rate of cattle	0.57	1/year
Birth rate of goats	1	1/year
Carrying capacity of rangeland (reference value)	29.6	Ha/AU
Cattle per labor unit	100	Cattle/person
Cheese production per goat (reference value)	21	Kg/year
Common lands area ("Ejido")	69,873	ha
Economically active population	0.34	Dimensionless
Emigration rate of population (reference value)	0.02	1/year
Labor per unit area in irrigated land	1	Persons/ha
Number of "ejidatarios" (users of common lands)	60	Persons
Number of goats per labour unit	133	Goats/person
Population birth rate	0.031	1/year
Population death rate	0.0095	1/year
Private property area	36,800	ha
Production per hectare for reference crops	2,663	Kg/ha
Sale rate of adult goats (reference value)	0.05	1/year
Sale rate of cattle	0.19	1/year
Sale rate of young goats (reference value)	0.5	1/year
Total predation of cattle (in drought periods)	400	Cattle/year
Total predation of goats (in drought periods)	1,000	Goats/year
Weight of cattle for sale	250	Kg/cattle
Weight of goat for sale	12	Kg/goat

CAPÍTULO 2

*Don José Jesús Ceseña Salgado regando su huerta (fotografía de Wendi Domínguez)

Resilience of small-scale social-ecological systems: trade-off and synergies of global and regional changes

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Enviado a *Global Environmental Change*:

Tenza A., Martínez-Fernández J., Pérez I., Giménez A. Resilience of small-scale social-ecological systems: trade-off and synergies of global and regional changes. *Submitted to Global Environmental Change*.

Abstract

Cross-scale interactions of environmental and socio-economic changes challenge the adaptive capacity of small-scale social-ecological systems. Understanding the interlinked effect of changes on global and regional scales to local dynamics is crucial for system resilience and adaptability. Using the System Dynamics approach, we developed a dynamic simulation model to: i) quantitatively analyze the causes of decline in a small-scale agro-system in Mexico; ii) measure the effects and the relative weight of the external drivers (i.e. regional drivers and global drivers) on the decline process; iii) identify and quantify cross-scale interactions. We developed our model based on local knowledge (and local ecological knowledge), and successfully simulated the historical behavior of the main variables associated with the decline process. Our simulation showed that the external drivers linked to global drivers, especially climatic drivers, more strongly influenced the system's behavior (i.e. population trend, irrigated land, livestock activity and local economy) than the regional drivers (i.e. regional development policies). The reinforcing relation between the effects of variability of rainfall and the volatility of market prices warns about the system's vulnerability to the double climate change and globalization exposure. Despite the importance of the external drivers to understand the system's historical behavior, endogenous structures (i.e. local conditions and feedbacks) were responsible for the system's decline. The interaction of socio-economic and environmental changes on multiple scales, along with the system's endogenous structure, are critical for the resilience of small-scale social-ecological systems. The complexity of these interactions challenges the adaptive capacity of small-scale agrosystems. Research into how endogenous factors model the consequences of climate change and current uncertainty about global markets is critical to improve the adaptive capacity of small-scale agrosystems and global food security.

Keywords: System dynamics, cross-scale interactions, drivers of change, vulnerability, arid environment, oasis

INTRODUCTION

Cross-scale interactions of environmental and socio-economic changes generate unexpected behaviors in complex systems, including feedbacks, synergies and trade-offs, which challenge the adaptive capacity of social-ecological systems (SESs, Allen 2014, Nayak and Berkes 2014, Eakin *et al*. 2009, Eakin 2005). The effects of these interactions on the resilience and adaptive capacity of small-scale agro-systems are especially important for global food security (O´Brien and Leichenko 2000, Young *et al*. 2006, Janssen *et al*. 2007, FAO 2014, Pérez *et al*. 2016). The adaptation of long-lived SESs to specific variability in natural resources and regular disturbances can hinder their capacity to adapt to new changes that occur on larger scales (Berkes *et al*. 2003, Janssen *et al*. 2007). Understanding the way changes on regional or global scales interact and affect small-scale systems is, thus, crucial for system resilience and adaptability (Folke 2006, Young *et al*. 2006, Allen *et al*. 2014). One well-known example is the so-called green revolution. The agricultural research programme designed to increase the agricultural production with modern and technician agriculture on a global scale caused profound negative externalities on regional and local scales (Pimentel *et al*. 1992, Srivastava *et al*. 2016) by eroding the resilience of small-scale agro-systems that were well adapted to local conditions (Silva *et al*. 2010). Here we quantitatively analyze the effect of environmental and socio-economic changes on global and regional scales to the resilience of small-scale, long-lived SESs.

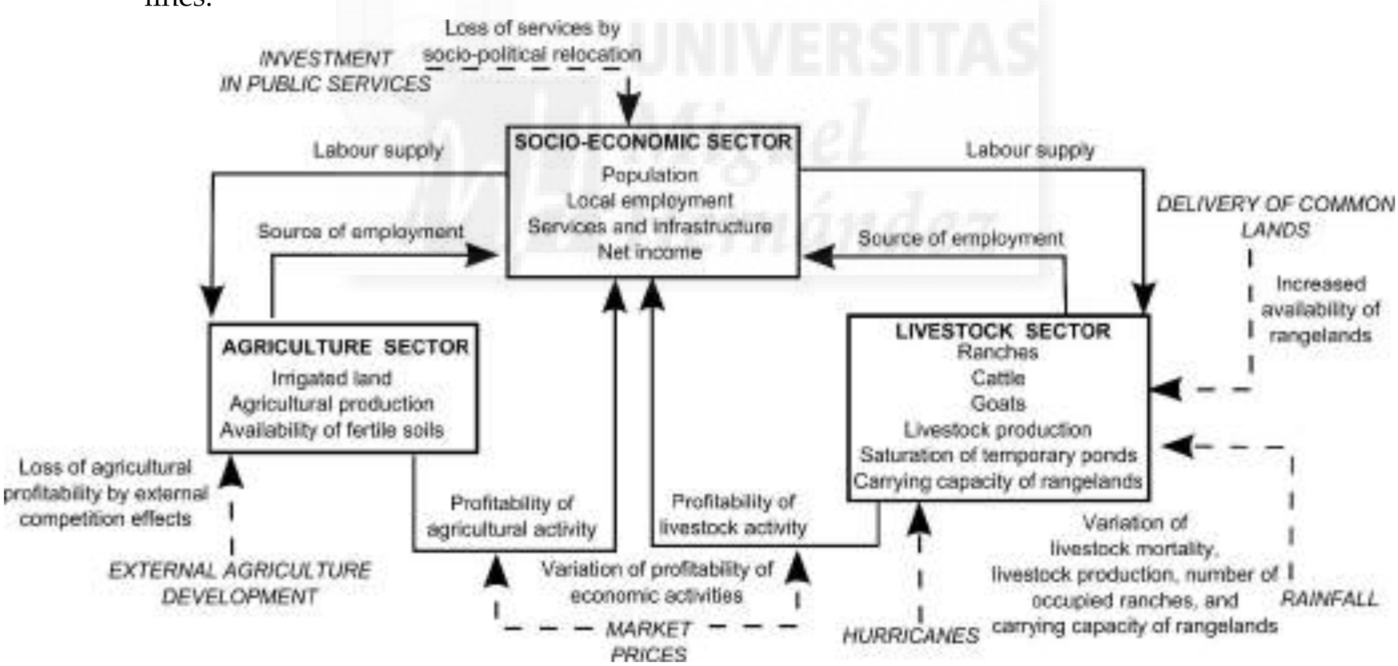
In the last few decades, many researchers have made the effort to understand social-ecological changes and the interplay between scales by using conceptual models, like adaptive cycles (Holling 1987, 2001, Abel *et al*. 2006) and panarchy (Gunderson and Holling 2002, Allen *et al*. 2014), where, similarly to ecosystems, SESs move through phases of growth and capital conservation, followed by phases of release (or collapse) and reorganization. Each system is also embedded in a nested hierarchy of adaptive cycles on multiple scales. Dynamics on smaller scales is faster and induce changes in higher scales, known as “revolts”. However, dynamics on larger scales is slower and stabilizes dynamics on smaller scales with the accumulated memory of system dynamics. Despite the theoretical usefulness of these approaches for identifying thresholds between regimes, discontinuity, novelty and cross-scale phenomena, they still entail a high level of abstraction that hinders the operationalization of these insights in case-specifics studies (Allen 2014). Some empirical studies have qualitatively shed some light on the effects of changes on different scales on the dynamics of SESs (Bunce *et al*. 2009, Mix *et al*. 2015), the vulnerability of SESs to multiple stressors or to double exposure (i.e. climate change and globalization process, Eakin 2005, Eakin *et al*. 2009), and the cross-scale interactions as a two-way process (i.e. top-down and bottom-up, Nayak and Berkes 2014). However, there is a risk in making policy recommendations from qualitative or conceptual models (Vennix 1996, Challies *et al*. 2014). Place-based, long-term, social-ecological research, and more formal approaches that include the uncertainty and complexity that are inherent to these systems, are thus needed to analyse and manage specific sustainability problems of SESs (Peterson *et al*. 2003, Young *et al*. 2006, Carpenter *et al*. 2012, Balvanera *et al*. 2017). To cover this need, we herein used the system dynamics approach.

The system dynamics approach and dynamic simulation models, historically used for analyses from industrial problems to world problems from a comprehensive point of view (Forrester 1958, 1973, Meadows *et al*. 1972), can be a useful methodological alternative to advance in the research agenda to study SESs. Dynamic simulation models have been previously used to analyze land-use changes (Duffy *et al*. 2001, Martínez-Fernández *et al*. 2000, Vidal-Legaz *et al*. 2013), sustainability assessments (Saysel *et al*., 2002, Banos *et al*. 2015, 2016), wildlife management (Perez *et al*. 2012), or water management (Xiao-Qing *et al*., 2012, Sanga and Mungatana 2016). Most of these previous studies focused on regional or river basin levels, and the time horizon under study regularly involved a short and recent period. Data scarcity is usually described as a limitation to develop quantitative models of small-scale systems (Duffy *et al*. 2001, Sanga and Mungatana 2016). Despite the relevance of small-scale agrosystems for global food security, institutional diversity or the sustainable use of natural resources, there is a gap in long-term quantitative studies on the causes of the decline of small-scale SESs, cross-scale interactions and the effects of changes at higher scales on the dynamics of these SESs.

Our study builds on a previous qualitative model about the SES of the oasis of Comondú, located in Baja California Sur (BCS), Mexico (Tenza *et al*. 2017). The oasis of Comondú, among other missional oases of BCS, was one of the first places where human populations permanently settled in the Baja California Peninsula, and where agriculture and livestock activities were successfully undertaken at the beginning of the 18th century (Cariño 2001, Cariño *et al*. 2016). Oases played a central role in this region's economy and culture. However, changes took place since halfway through the past twentieth century. Poorly connected oases, like the oasis of Comondú, were marginalised (Cariño *et al*. 2016). As in other rural areas in the world (Collantes and Pinilla 2004, Collantes 2007), they have lived through a serious depopulation process that threatens their existence in the long term (a reduction of 75% from 1940 to 2010).

Tenza *et al*. (2017) posed a general hypothesis about the structure of this SES responsible for problematic behavior (i.e. the decline process), and a set of dynamical hypotheses about the effects of the regional and global drivers on the dynamics of this SES. According to Tenza *et al*. (2017), the endogenous structure is dominated by positive feedbacks between the socio-economic sector and the main productive activities (i.e. agriculture and livestock activity). Only the environmental limits to productive activities (i.e. fertile soil and the carrying capacity of rangelands) act as negative feedback by regulating growth dynamics (Fig. 1). Historically, this SES has been exposed to global drivers, like global markets and climate conditions (rainfall, droughts, and tropical cyclones or hurricanes). However since the 1940s, a set of regional development policies has been implemented, which involve: i) agrarian change (i.e. development of more technical and modern agriculture in BCS); ii) public investment changes (i.e. reduction in public services in the oases, increased public services in coastal areas and tourism centers of BCS); iii) property right changes (i.e. delivery of common lands to landless people by the creation of "ejidos").

Figure 1. Conceptual diagram of the social-ecological system of the oasis of Comondú. The main sectors are shown in boxes. The external drivers are in italics and capital letters, and their effects on local dynamics are indicated with dashed lines.



Regarding the effects of these regional and global drivers on the dynamics of this SES, Tenza *et al*. (2017) defined five main dynamical hypotheses: i) the agrarian change affected the profitability of the traditional agriculture in the oasis by reversing the positive feedbacks of this SES from growth to decline; ii) the agrarian change and the public investment changes encouraged the oasis population to migrate; iii) the delivery of common lands boosted the relative weight of livestock activity, halted migration, improved local economy and increased local employment; iv) the extreme dependence on livestock activity increased this SES' vulnerability and sensitivity to the variability of climate conditions (e.g. extreme weather events like droughts and hurricanes); v) market prices affected the profitability of productive activities by making the livestock activity by far the most profitable.

We herein develop a system dynamic model to test the hypotheses proposed by Tenza *et al*. (2017) and to respond to the following key questions for system resilience: What is the relative weight of the effects of changes on higher scales on the decline of this small-scale SES? Which drivers have influenced heavily the dynamics of this system, global ones or regional ones? Are there cross-scale interactions between the global and regional drivers (i.e. synergies or trade-offs)? To our knowledge, this is the first study to attempt to quantitatively analyze the causes of decline of a small-scale SES, to measure the effects and relative weight of external drivers, and to identify and quantify cross-scale interactions. We used local knowledge (and local ecological knowledge), acquired from local inhabitants, to overcome data scarcity on the local scale. Our resulting model shows the usefulness of the system dynamics approach to formally explore key issues of the resilience framework. In light of our results, we claim the importance to advance beyond conceptual models in the study of SESs.

METHODS

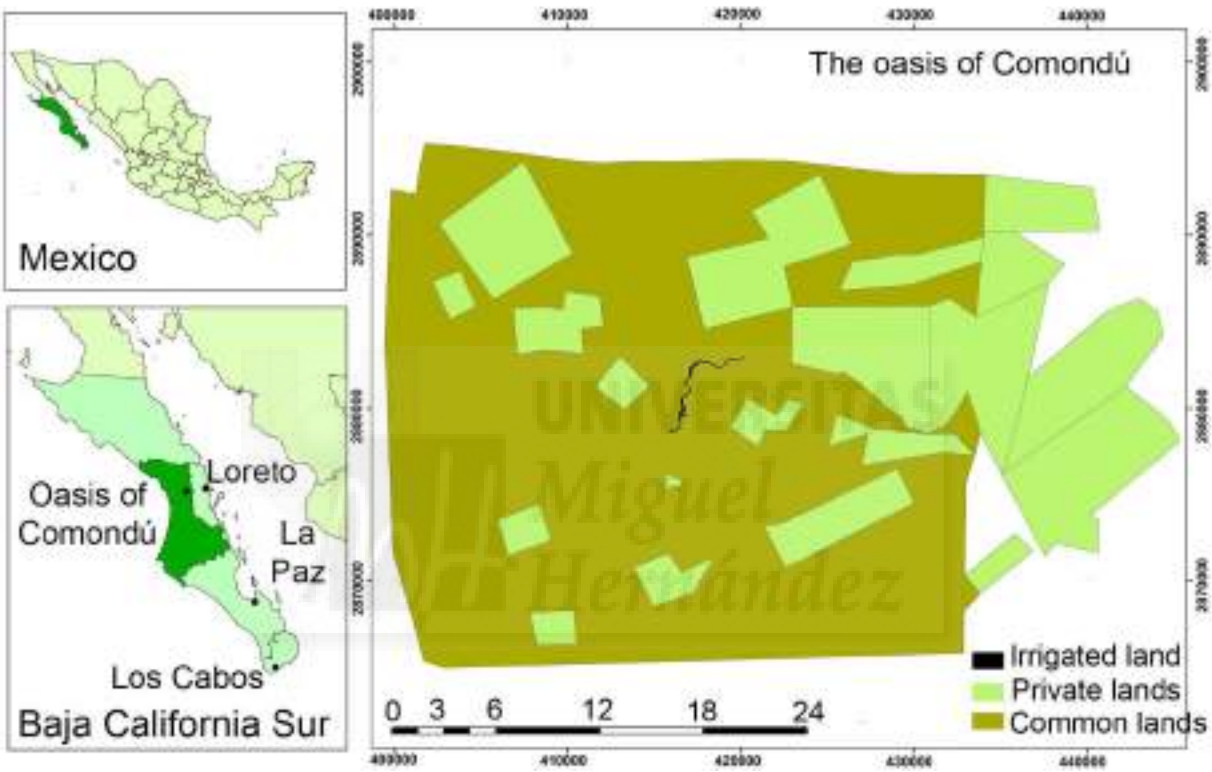
Here we provide details of how we developed the dynamic simulation model SESSMO (from the acronym "Social-Ecological System Sustainability Model") and how we used it to better understand the structural causes of the dynamics of the SES as a result of socio-environmental changes on regional and global scales. The system dynamics approach focuses on the structure of complex systems and their behavior. Complexity emerges from the non-linear relationships that link system components, feedbacks, and material or information delays (Roberts *et al*. 1983, Vennix 1996, Sterman 2000, Jørgensen and Bendoricchio 2001). In this section, we provide details of the study system, the model description, model testing, and the simulations that we ran. We developed SESSMO using the Vensim DSS 6.4c software (Ventana Systems).

Study system

The oasis of Comondú is located in the municipality of Comondú, in the Sierra de La Giganta mountain range (Fig. 2). The study area covers 107,080 ha, which includes 80 ha of irrigated land inside the oasis, and 70,000 ha of communal land and 37,000 ha of private land in the immediate surroundings, which are environmentally and socio-economically linked to the oasis. The last two large areas are used for ranching and they depend on erratic rainfall.

Irrigated agriculture depends on the groundwater that emerges from several springs scattered throughout the oasis. The average annual rainfall in the area is 175 mm, but tropical cyclones and droughts are frequent in this region and strongly influence its productivity (Tenza *et al*. 2017). According to the 2010 census, there are 257 inhabitants. See Tenza *et al*. (2017) for a more detailed description of the study system.

Figure 2. Map of the study area in Baja California Sur (Mexico) with details of the irrigated land, private and common lands of the oasis of Comondú.



Data collection

To develop SESSMO we used qualitative and quantitative data to: i) define the main relationships among the system components; ii) build the reference mode of the main model variables (i.e. the real behavior of the system variables defined by the observed data); iii) define the model parameters; iv) create the data series of the external drivers (external variables or forcing functions). The information and data used to develop the model was obtained in 2010-2012 during four fieldwork stays that lasted from 15 days to 4 months. The data sets of climate, population and market prices were obtained from different government agencies in Mexico. Household-type information and local ecological knowledge (e.g. dynamics of productive activities, local availability of services, local strategies to cope perturbations) were obtained by in-depth interviews and participant observations over a

5-week period in the local communities of the oasis of Comondú. For a more detailed description of the data collection process, see Tenza *et al*. (2017). The main relationships of the system components and the definition of the reference mode can be found in Tenza *et al*. (2017).

Model description

SESSMO simulates the main dynamics of the SES of the oasis of Comondú from 1940 to 2010 with annual resolution. The model has five principal variables (i.e. stock variables): human population, area of irrigated land under production, number of occupied ranches, cattle and goats. Table 1 shows the initial values and units for these stock variables. There are 39 parameters, only six are related to time delays, effects and weighting factors, which were defined by the automatic calibration tools of Vensim. The model has 12 external drivers, which include market prices, minimum wage data, annual rainfall, hurricanes, and regional development policies (i.e. public services, external agriculture development, delivery of common lands). In order to facilitate the description and understanding of the model, we divided the model into three sectors: socio-economic, agriculture and livestock. A complete description of the parameters, equations and external drivers is presented in Appendix A. The conceptual model that underlies this structure is briefly presented in Figure 1 (see details in Tenza *et al*. 2017).

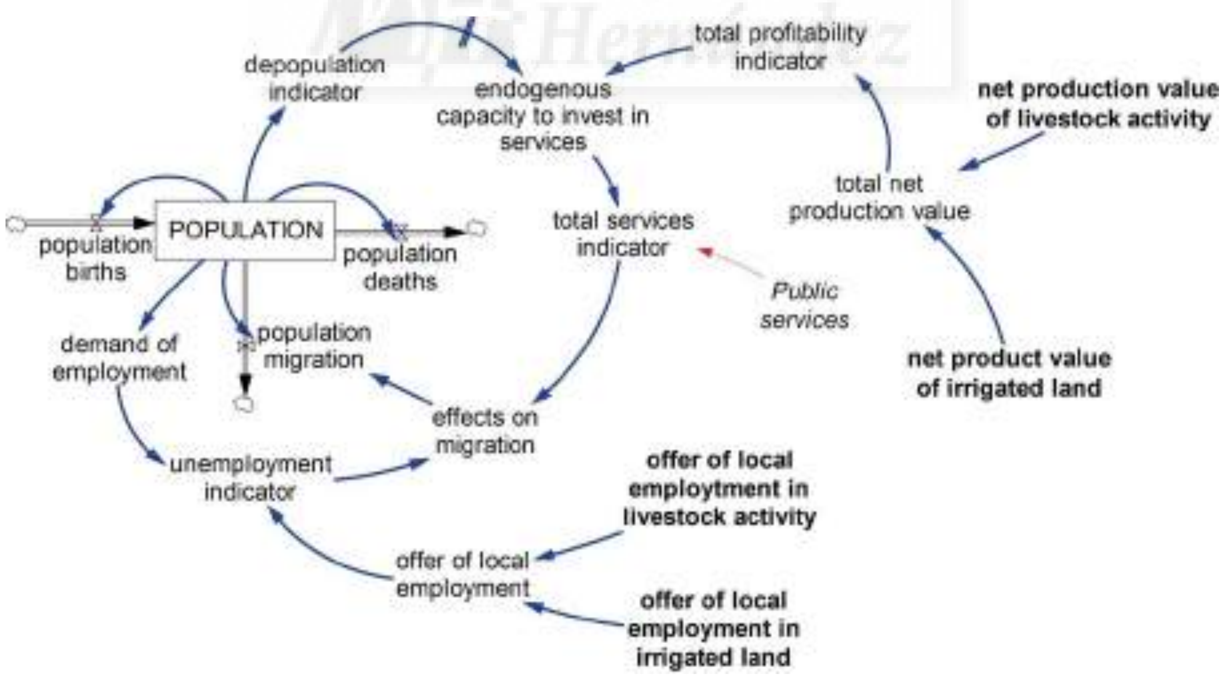
Table 1. Initial values and dataset sources for the stock variables of SESSMO.

Sector	Variable	Initial value	Units	Source
Socio-economic	Population	1,006	people	National Geostatistical Framework (INEGI 2011)
Agriculture	Irrigated lands	78.9	ha	Estimated from interviews and GIS data
Livestock	Ranches	38	ranches	Estimated from interviews and GIS data
	Goats	0	goats	Estimated from interviews and data from an agricultural census of 1962
	Cattle	760	cattle	Estimated from interviews and data from an agricultural census of 1962

Socio-economic sector

The socio-economic sector of the model is summarized in Figure 3. *Population* is the stock variable of this sector and is defined by the input flow of *population births* and the output flows of *population deaths* and *population migration*. Migration is affected by unemployment and total services indicators. The greater unemployment becomes, the higher the migration rate. The *offer of local employment* is defined by the labor needed in economic activities (i.e. the agriculture and livestock activity). The *total services indicator* describes availability of services. The greater the availability of services, the lower the migration rate. Availability of services in the oasis depends on two variables: the *endogenous capacity to invest in services* and *public services*. The first is a qualitative index that depends on the profitability of economic activities *(total profitability indicator*) and the availability of human capital to maintain institutions and community works (*depopulation indicator*). The *total profitability indicator* is defined by *the total net production value* which, in turn, depends on the *net production value of irrigated land* and the *net production value of livestock activity*. *Public services* is an external driver, a qualitative index that represents the observed availability of services that comes from external public investment (education, health, security, communications and transportation).

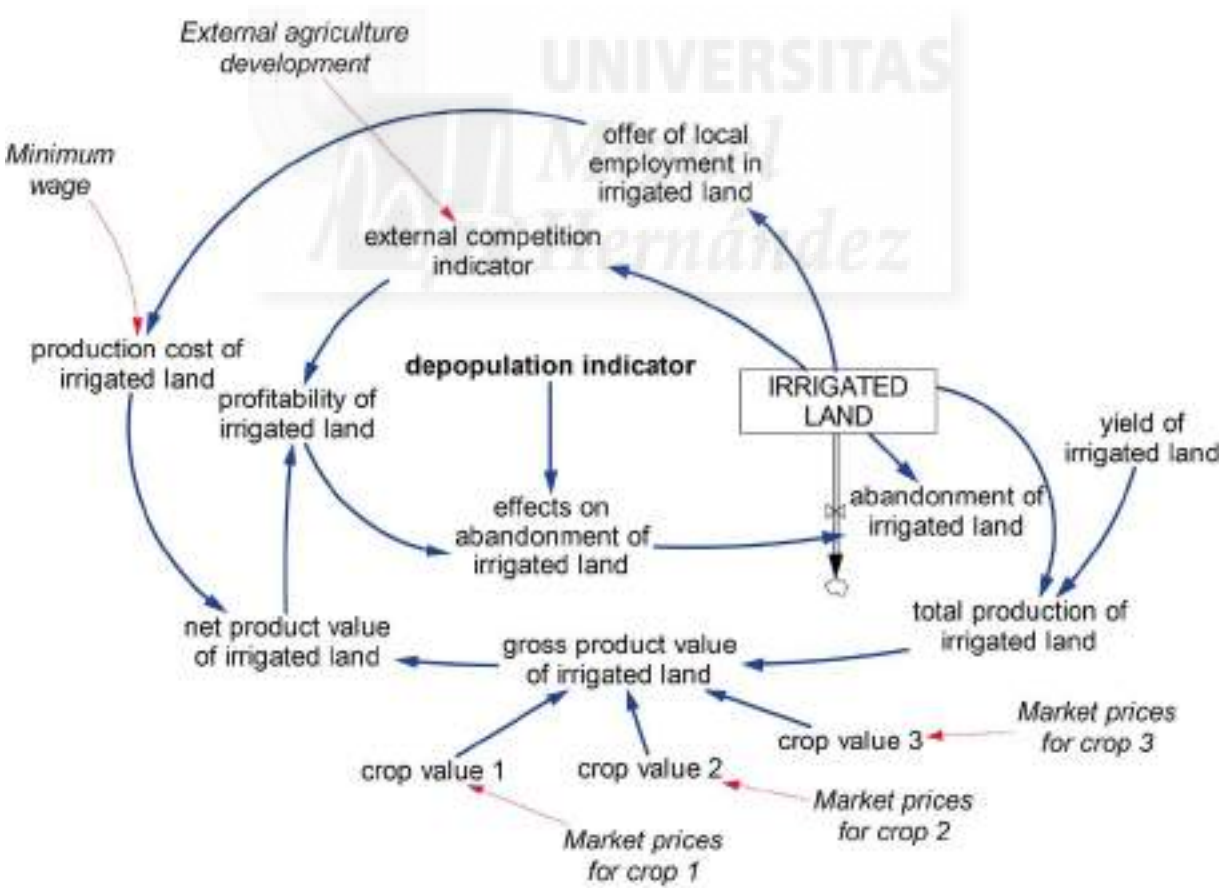
Figure 3. Simplified flow chart of the socio-economic sector. The stock variables are shown in boxes. Pipelines are the input and output flow variables. The external drivers are marked in italics and their interactions are indicated with red arrows. The variables shown in bold link the different sectors. The variables between the "lower than/higher than" symbols represent the variables located in the distant places of the same diagram.



Agriculture sector

Figure 4 shows the simplified flow diagram of the agriculture sector. The stock variable is *irrigated land* which only has an output flow that defines the abandonment process. *Abandonment of irrigated land* is modified by the effects of *the profitability of irrigated land* and by the depopulation process, both measured by indicators. The lower *profitability of irrigated land*, the greater the *abandonment of irrigated land*. The *depopulation indicator* affects the abandonment process in economic activities, agriculture and livestock. It represents the attraction effect of the migrant networks in urban centers of the state, especially kinship (chain migration) (Davis *et al*. 2002).

Figure 4. Simplified flow chart of the agriculture sector. The stock variables are shown in boxes. Pipelines are the input and output flow variables. The external drivers are marked in italics and their interactions are denoted by red arrows. The variables in bold link the different sectors. The variables between the "lower than/higher than" symbols represent the variables located in the distant places of the same diagram.



Profitability of irrigated land is obtained from the *net production value of irrigated land*, which is affected by *the external competition indicator*. This indicator is a qualitative index that depends on the *irrigated land* and *external agriculture development*. The greater *external agriculture development*, the lower the *external competition indicator*, and the lower the *profitability of irrigated land*. The model calculates the *net production value of irrigated* land by taking into account the gross production value and the production cost. The *production cost of irrigated land* depends on the labor engaged in irrigated land and the *minimum wage*. The *gross production value of irrigated land* is defined by the *total production of irrigated land*, which depends on *irrigated land* and the *yield of irrigated land*, and the market prices for the main representative crops (i.e. sugar cane, grapes and dates).

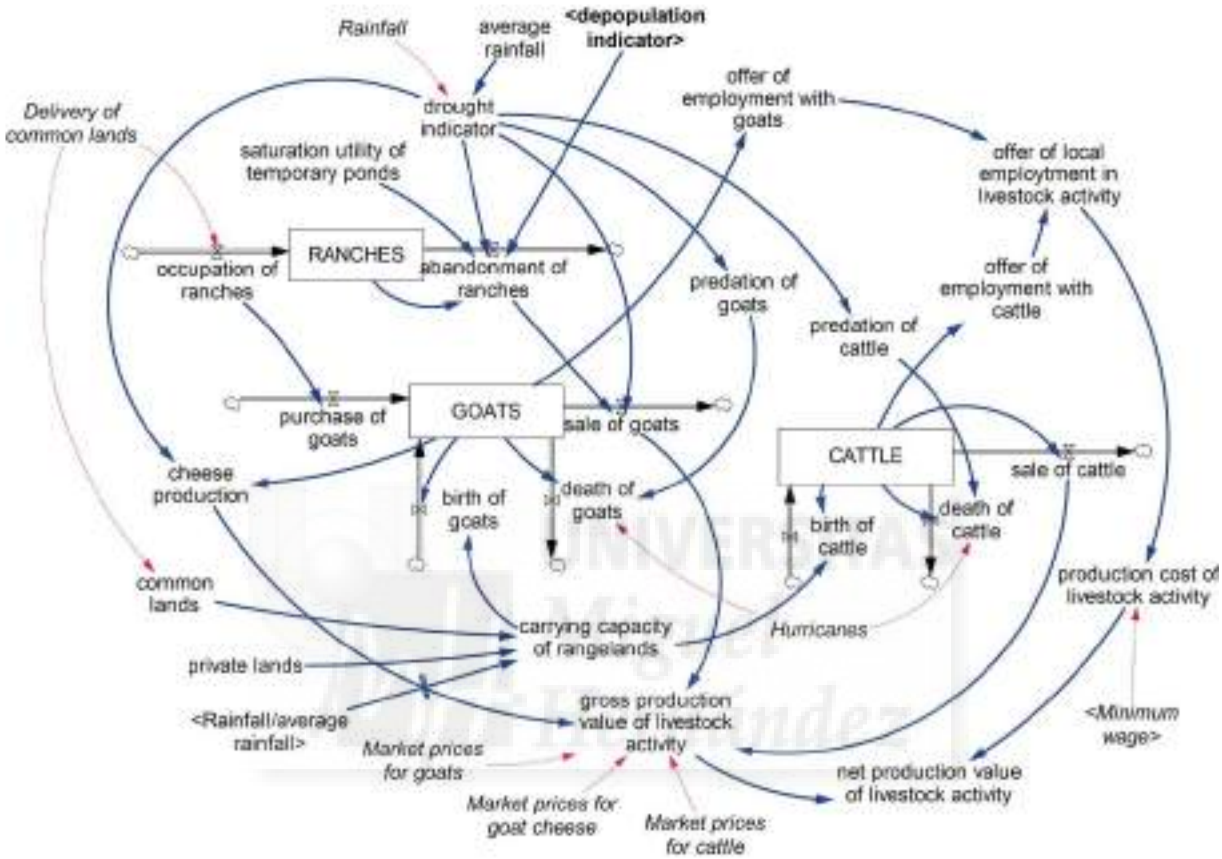
The agriculture sector has a labor shortage indicator, which detects if the population falls under the minimum labor needed to maintain irrigated land. If population falls under this minimum, there is an abandonment of irrigated land because it cannot be maintained.

Livestock sector

This sector has three stock variables: ranches, cattle and goats. Goats did not enter the system until 1959, as a result of the success of goat herding in neighboring oases (Conway 2013). The simplified flow chart of the livestock sector is presented in Figure 5.

The ranches stock is defined by the occupation of ranches and abandonment of ranches. The number of occupied ranches increases with the delivery of common lands, which represents the creation of the ejido Comondú in 1968. Abandonment of ranches depends on three factors: the drought indicator, the saturation utility of temporary ponds, and the depopulation indicator. Saturation utility of ponds reduces the likelihood of engaging in itinerant grazing (a local strategy to cope with drought periods). If saturation of ponds takes place, the number of ranches is adjusted to the economically sustainable number of ranches, which depends on livestock stocking and the size of the herds that are profitable for ranchers. The greater the intensity of drought, the more marked the adjustment of the number of ranches. There is drought when the accumulated rainfall of 2 years is below the average rainfall for the study period. The intensity of drought is measured according to a maximum value in the drought severity index (Sancho & Cervera *et al*. 1980). Rainfall also modifies the carrying capacity of rangelands (i.e. it declines as rainfall decreases), which is also defined by the area of private and common lands. The carrying capacity of rangelands affects the births of cattle and goats by a denso-dependency effect that lowers births as stocks reach the limits, but never lowers to 0, by allowing some overload, according to the more realistic behavior of livestock systems.

Figure 5. Simplified flow chart of livestock sector. The stock variables are shown in boxes. Pipelines are the input and output flow variables. The external drivers are marked in italics and their interactions are indicated with red arrows. The variables shown in bold link the different sectors. The variables between the "lower than/higher than" symbols represent the variables located in the distant places of the same diagram.



Goats and cattle stocks are also defined by the output flows of deaths and sales. With goats, there is an input flow of purchase of goats associated with the delivery of common lands and the occupation of new ranches. Livestock mortality (goats and cattle) is affected by droughts and hurricanes, and by predation by coyotes, cougars and bobcats. Predation of livestock occurs during drought periods. The greater the intensity of droughts and hurricanes, the higher livestock mortality becomes. Sale of cattle is a simple output flow defined by the sale rate of cattle. For goats, the sale is composed of the sale of young goats, which is the most important, the sale of adult goats, which is a sale of discarded animals (too old or sick), and the sale of small herds, which result from abandonment of ranches. Droughts increase the sale of young and adult goats to reduce maintenance costs (another local strategy to cope with drought periods). Another goat herding product is cheese. Ranchers produce cheese every 2 weeks from October to May in wet years and from October to March in dry years. Cheese production in the model is affected by droughts. The net production value of livestock (cheese production and sale of goats and cattle) is computed following a similar approach to that of the net production value of irrigated land.

The livestock sector, like the agriculture sector, has labor shortage indicators for ranches, goats and cattle. If the population falls below the minimum needed to maintain these stocks, then abandonment of ranches comes into play, with the sale of goats and cattle.

Model testing

In order to determine the confidence level in the model, we checked the model's robustness, reliability and validity by means of structural tests, sensitivity analyses and behavioral tests (Barlas 1989, 1996, Graham *et al*. 2002, Solecki and Oliveri 2004, Andarzian *et al*. 2011, Li *et al*. 2012).

Most of the confidence levels in these models are measured in terms of the ability to simulate the expected logical behavior in the real system, even beyond the conditions under which the model was calibrated. To verify this, we checked consistency in model units, we extended the time horizon to identify possible anomalous behaviors in the long run, and we performed a set of extreme conditions tests to check internal model consistency. The model's behavior must be defined by the endogenous structure (e.g. relations and feedbacks), and not by the model's parameters. The model's robustness is measured in terms of maintaining the behavioral patterns of the main variables (i.e. target variables, stock variables in our case) despite major changes in the model's parameters.

Measuring the goodness of fit between the simulated and the observed data is a necessary, but not a sufficient, feature to determine the confidence in the model. Among the behavioral tests, we used Theil's U statistics, which is a set of statistical goodness-of-fit measures that are suitable for dynamic system models (Sterman 1984, Oliva 2003).

A more detailed description of the model testing procedure is presented in Appendix B.

Effects of the regional and global drivers

We developed a set of experimental simulations to assess the effects of the regional and global drivers on the system's dynamics, and to identify trade-offs and synergies between them (cross-scale interactions). We made 15 additional simulations, apart from the base simulation (*baserun*, presented in Section 3.1), in which the effects of each external driver, or a combination of them, were removed to identify the specific effects of these drivers on the model's dynamics. These experimental simulations represent hypothetical scenarios of the past. We classified 14 of these simulations into two groups: regional drivers and global drivers. The first group included: i) the non-agrarian change in BCS (*no external agriculture development*); ii) no change in public investment (*constant public services*), whose initial values remained; iii) no change in property rights (*no ejido*); iv) all their possible combinations. The second group included: i) maintenance of market prices according to their mean values (*constant market prices*, we also considered maintenance of a minimum wage); ii) the suppression of rainfall variability (*constant rainfall*), remaining it constant according to the mean value; iii) no hurricanes occurring (*no hurricanes*); iv) all their possible combinations. The last experimental simulation showed the system's behavior after removing the effects of all the external drivers (*without all the external drivers*; see Appendix C for details).

We assessed the effects of the external drivers by comparing the experimental simulation results with the *baserun* (see the equation to calculate the variation coefficients in Appendix C). Comparisons focused on the value at the simulation end time for the following target variables: *population*, *total services indicator*, and *unemployment indicator* as they are most directly linked to the decline of the Comondú SES. We also compared the mean and standard deviation for these variables in each simulation.

Trade-off and synergies

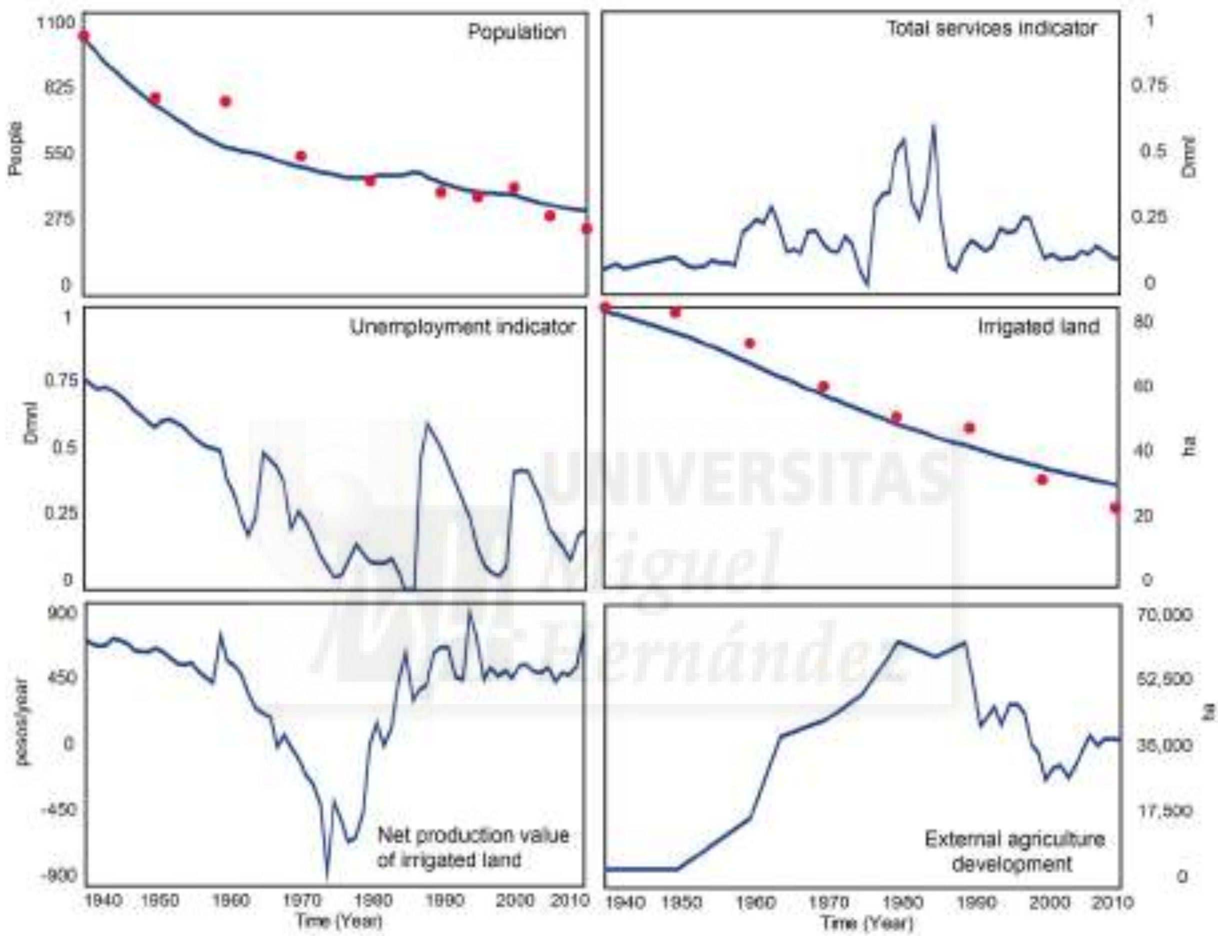
We explored the potential cross-scale interactions, synergies and trade-offs among the external drivers. Synergies happen when the combined effect of the external drivers is higher than the sum of their separate effects. Trade-offs occur when the combined effect of the external drivers is lower than the sum of their separate effects (Luukkanen *et al*. 2012). The comparison made between the expected and actual results served as an indicator of the existence of synergies, trade-offs or delinking. In this case, comparisons focused on the mean value of the target variables throughout simulations since it provides a better representation of the overall trend than the value at the simulation end time.

RESULTS

Results of the base simulation

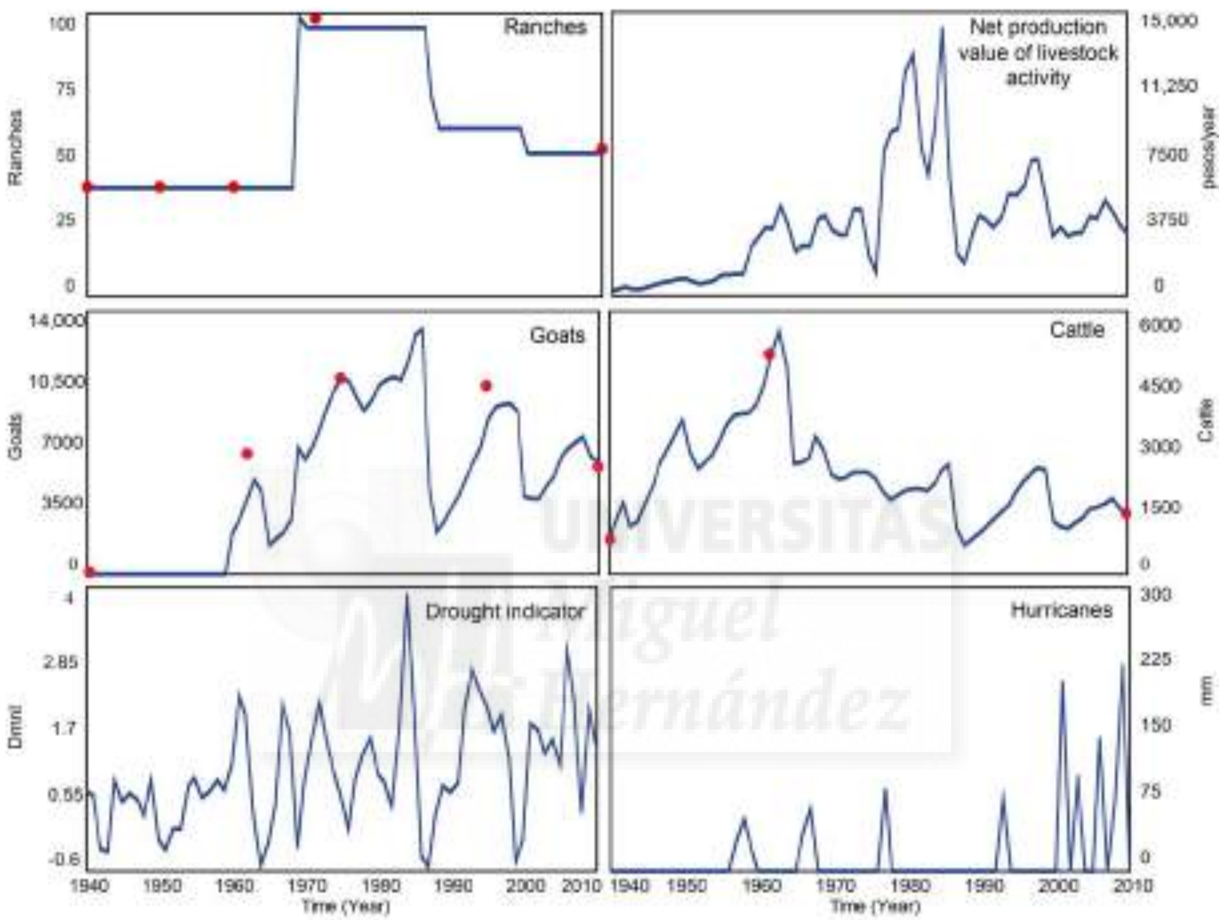
Figure 6 depicts the behavior of *population* and *irrigated land* with some socio-economic indicators, which are closely associated with these stock variables: *unemployment indicator*, *total services indicator*, *net production value of irrigated land*, and *external agriculture development*. The behaviors of *ranches*, *cattle* and *goats* are displayed in Figure 7, and are accompanied by other relevant indicators for livestock activity, such as *drought indicator*, *hurricanes* and the *net production value of livestock activity*.

Figure 6. The base simulation results for: *population*, *total services indicator*, *unemployment indicator*, *irrigated land*, *net production value of irrigated land*, and *external agriculture development*. Blue lines represent the simulated data. Red points are the observed data.



The *baserun* simulation shows the population decline, which slightly halted between the 1970s and the 1980s, and coincides with a peak in the total services indicator and a fall of the unemployment indicator (Fig. 6). These changes in unemployment and the total services indicator are explained mainly by the livestock activity dynamics, which reaches its highest level of occupied ranches and goat stocking during this period (Fig. 7). The rise in livestock activity was caused by the delivery of common lands in 1968, which implied the entry of 60 new ranchers. The subsequent fall in services and rise in unemployment explain the continuing population decline after this period. These last changes were caused by the major fluctuations in livestock activity as a result of droughts and hurricanes. Almost 50 ranches were abandoned during the droughts of the 1980s and the 1990s (Fig. 7), which coincides with the historical behavior described in the interviews (Tenza *et al*. 2017). Stronger hurricanes took place in the last decade of the simulation period (Fig. 7).

Figure 7. The base simulation results for: *ranches*, *net production value of livestock activity*, *goats*, *cattle*, *drought indicator*, and *hurricanes.* Blue lines denote the simulated data. Red points are the observed data.



Irrigated land declines throughout the simulation period (Fig. 6). External agriculture development suggests a strong competition effect on the profitability of irrigated land since the 1950s. The sharpest fall in profitability occurred in the 1970s, when, apart from external competition effects, a fall in all the market prices and a rise in labor costs were recorded. The most profitable was by far the latter when comparing the net production value of irrigated land and livestock activity.

Both indicators (unemployment and total services) indicated that the initial conditions were not favorable for the local population, and the best values for them were obtained after the rise in the relative weight of livestock activity between the 1970s and the 1980s (Fig. 6).

Model testing results

The model successfully passed the main structural tests with no unexpected behaviors, and the sensitivity analysis revealed the model's high robustness. The basic behavior pattern was maintained, despite some major changes in the parameters. These results boosted our confidence in the model, especially after checking that variations in parameters with greater uncertainty due to lack of knowledge did not cause any major changes in model outputs. The statistical assessment of goodness of fit indicated a good agreement between the simulated and the available observed data for the main model variables (see Appendix B for details).

Effects of global and regional changes

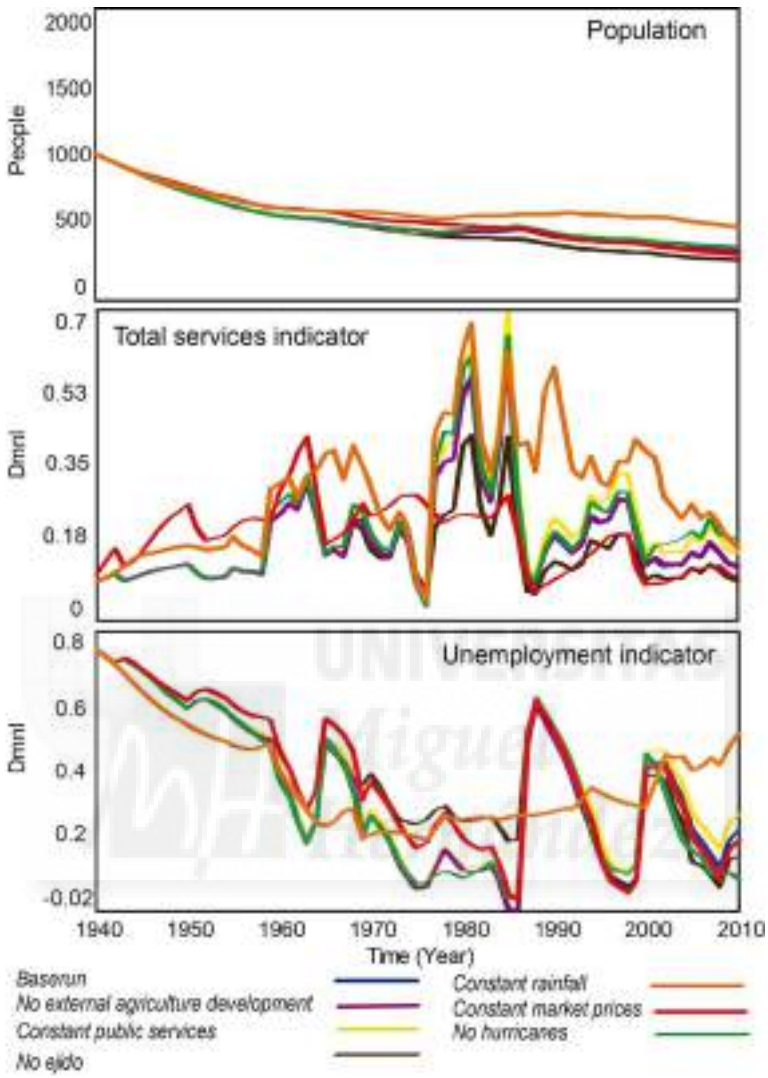
Figure 8 displays the behavior of the target variables (i.e. *population*, *total services indicator* and *unemployment indicator*) after removing each external driver separately.

The regional drivers barely had any effect on the overall SES dynamics (Fig. 8). The global drivers had stronger effects on the target variables. The *total services indicator* was markedly shaped by market prices, whereas the *unemployment indicator* was influenced mostly by rainfall variability. In the first case, this dependence was explained because the *total services indicator* was defined partially by the *total profitability indicator*, which depends on market prices. In the second case, it was explained because rainfall variability strongly affected the livestock activity dynamics, this being the main economic activity.

In the simulations "*no external agriculture development*" and "*constant public services*", *population* was larger than in the *baserun* by 2% and 7%, respectively. Unemployment was 12% lower in the simulation "*no external agriculture development*", whereas it was 23% higher in the simulation "*constant public services*".

Population at the end of the simulation "*no ejido*" was 17% lower than in the *baserun*. The *total services indicator* was 24% lower. We need to see changes in the mean value (that better represents the general trend of both the *total services indicator* and the *unemployment indicator*) to see that unemployment throughout this simulation was actually around 8% higher than in the *baserun* (Table 2). The no creation of the ejido would have generally implied a rise in unemployment. However without the ejido, the effects of droughts and hurricanes on local employment would have been lower in the last few decades.

Figure 8. Results of the experimental simulations. Effects of removing each external driver separately on the dynamics of the target variables: population, total services indicator, and unemployment indicator.



Population at the end of the simulation "*constant rainfall*" was 52% larger than in the *baserun*. The mean unemployment indicator value was also 7.7% higher. This result was explained because rainfall variability also included wet periods (i.e. years with rainfall above the average), which positively affect livestock activity by increasing employment and income. When considering the overall dynamics, rainfall variability helped increase employment throughout the simulation.

The simulation "*no hurricanes*" showed wider variations at the end time because the most intense hurricanes concentrated precisely in the last decade of the simulation. *Population* and *total services indicator* were larger than in the baserun by 57% and 11%, respectively, whereas unemployment was 67% lower than in the *baserun*. The mean values of the target variables displayed narrower variations.

Table 2. Variation coefficients of the experimental simulations, expressed as a percentage. For the comparison between the experimental simulations and the Baserun, we focused on the values of each target variable at simulation end time (t = 2010), its mean value throughout the simulation period and the standard deviation.

	Population			*Total services indicator*			*Unemployment indicator*		
Simulation name	End time	Mean value	Standard deviation	End time	Mean value	Standard deviation	End time	Mean value	Standard deviation
No external agriculture development	2.4	0.6	-1.6	5.2	1.0	0.7	-12.6	-2.5	0.9
Constant services	7.2	1.6	-4.3	26.1	11.4	14.8	22.7	4.3	-4.0
No Ejido	-16.9	-4.9	12.0	-24.0	-15.5	-27.3	-34.5	7.9	-11.9
Constant rainfall	51.8	18.4	-31.6	39.8	54.8	24.7	133.3	7.7	-33.9
No hurricanes	11.3	2.5	-5.8	56.6	10.7	10.4	-67.0	-3.2	2.2
Constant market prices	-4.0	4.9	3.7	-18.2	2.7	-31.0	-13.7	9.8	-4.1
Without all the regional development policies	-10.5	-3.3	8.1	-1.2	-6.3	-18.8	-30.0	8.5	-14.1
No external agriculture development + Constant public services	9.9	2.2	-5.7	32.9	12.7	15.7	11.3	1.9	-3.3
No external agriculture development + No Ejido	-14.8	-4.3	10.8	-19.9	-14.7	-27.0	-49.5	5.0	-9.4
Constant public services + No Ejido	-12.8	-3.9	9.3	-6.4	-7.2	-19.2	-15.9	11.3	-16.3
Without external drivers linked to global processes	77.0	38.8	-45.3	126.8	89.7	-21.3	45.3	28.3	-50.3
Constant rainfall + No hurricanes	81.7	23.5	-41.0	158.8	75.3	39.9	53.1	5.3	-36.5
Constant rainfall + Constant market prices	51.4	33.6	-33.1	17.5	72.7	-14.7	133.4	31.4	-51.5
Constant market prices + No hurricanes	5.6	7.3	-1.4	34.3	11.4	-30.4	-89.2	5.9	0.0
Without all the external drivers	38.3	30.8	-19.9	65.5	70.9	-7.0	62.9	42.2	-59.3

In the simulation "*constant market prices*", population, services and unemployment were lower than the in *baserun* at the simulation end time by 4%, 18% and 14%, respectively. However, the mean values of the target variables indicated the opposite; they increased by 5%, 3% and 10%, respectively. Maintaining market prices constant in general terms neutralizes the effects of droughts and hurricanes by increasing the average values of total services, employment and population. However at the simulation end time, market prices had a positive impact on ranches, which was lost when this external driver was removed.

Comparing the variance (standard deviation) of the target variables in the baserun and in each experimental simulation allowed us to deduce the variability that each external driver conferred to the target variables (Table 2). Rainfall was the external driver that provided wider variability to *population* and to the *unemployment indicator* (32% and 34%, respectively), whereas the variability of the *total services indicator* was more influenced by market prices (by 31%).

Trade-off and synergies

The combined effect of removing more than one external driver at a time helped us to identify the existence of trade-offs and synergies which operated cross-scale (i.e. from global to local). Figure 9 shows the behavior of the target variables after removing the regional development policies, the external drivers linked to global processes, and all the external drivers together (see the variation coefficients in Table 2).

The most visible result was found when removing the effects of all the external drivers as the general trend towards population decline improved, but did not stop. At the end of the simulation "*without all external drivers*", *population* was 38% higher than in the *baserun*, whereas population declined throughout the period 1940-2010, with changes from 68% to 55% from the *baserun* to the simulation without the external drivers. This difference in population decline can be interpreted as the relative weight of the effects of the external drivers on the entire depopulation process of this SES (around 19% of population decline can be explained by the effect of external drivers).

When only global drivers were removed, *population* at the end of simulation was 77% higher than in the *baserun*. If compared with the above experimental simulation, the effects of the global drivers were stronger than the effects of all the external drivers. Therefore, the regional drivers partially counter-balanced the effects of the global drivers.

Table 3 quantifies the encountered trade-offs and synergies.

Figure 9. Results of the experimental simulations. Effects of removing regional drivers, global drivers, and all the external drivers on the dynamics of the target variables: *population*, *total services indicator*, and *unemployment indicator*.

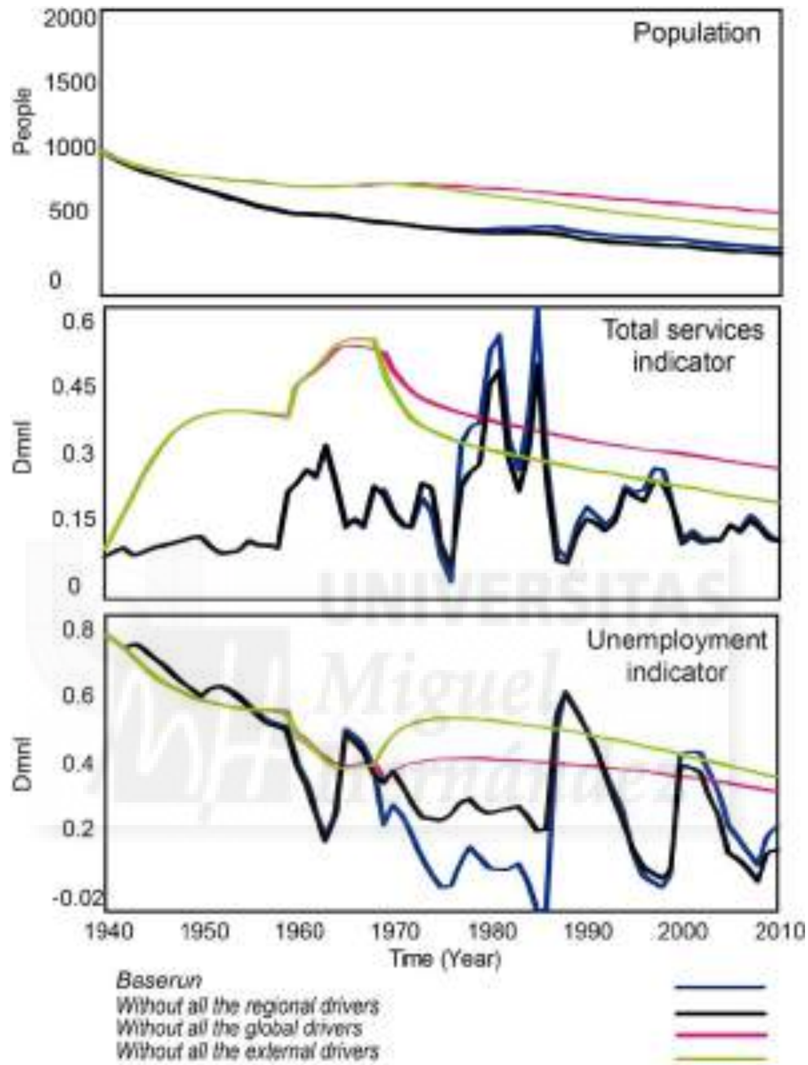


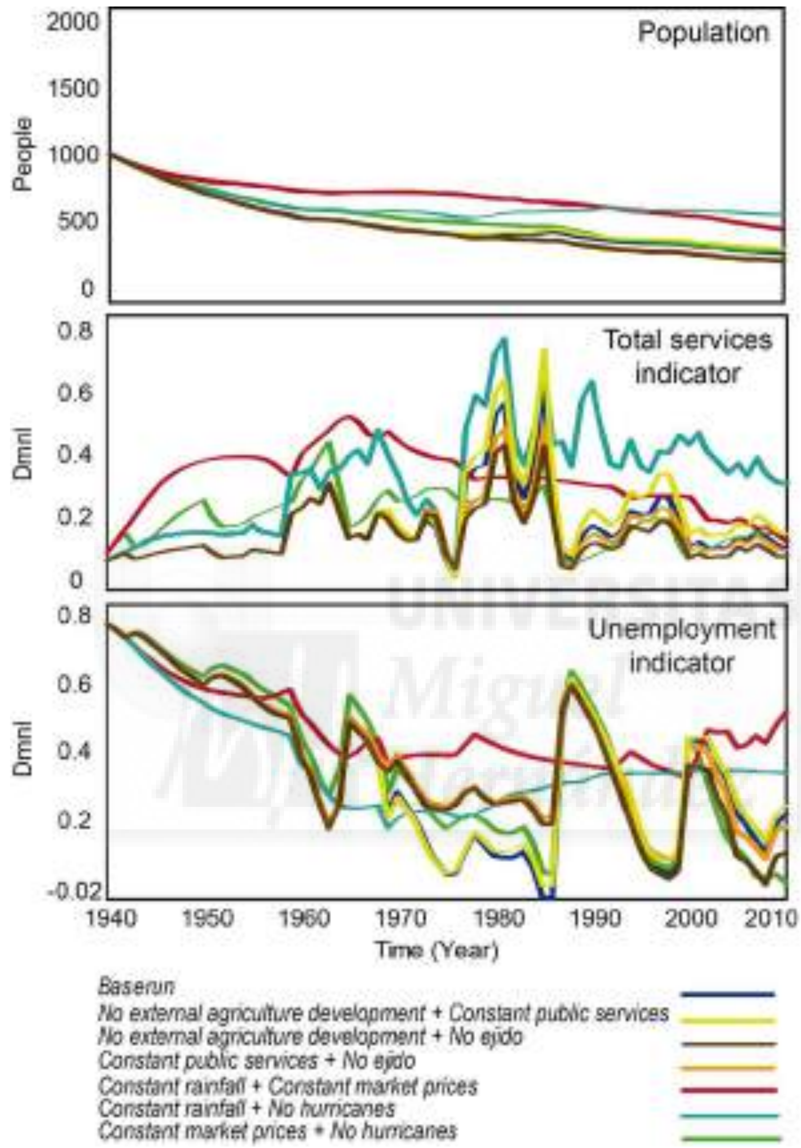
Figure 10 displays the behavior of the target variables after removing the external drivers by pairs in the two main groups (regional and global drivers).

Among the most remarkable trade-offs and synergies, we identified the synergic relation between rainfall variability and variability of market prices, which affected all the target variables (Table 3) and, to a lesser extent, between rainfall and hurricanes. The relations between the regional drivers were weaker. A synergic relation was observed between external agriculture development and maintenance of public investment. In contrast, the ejido Comondú produced a trade-off with them both.

Table 3. Trade-offs and synergies. Quantification is based on the differences between the expected and actual results of combining external drivers. The effects of external drivers are measured as variation coefficients, obtained by the comparison between the experimental simulations and the *Baserun* (see the variation coefficients in Table 2). The comparison focused on the variation coefficients of the mean value of the target variables (i.e. *population*, *total services indicator*, and *unemployment indicator*). The expected results are the sum of the variation coefficients of the experimental simulations that remove each external driver separately. The actual results are the variation coefficients of the experimental simulations that remove more than one external driver at a time. We considered that there was a synergy when the result was higher than 0, a trade-off when the result was lower than 0, and a delinking when the result equaled 0.

Combinations of external drivers	Population	Total services indicator	Unemployment indicator
Without all the regional policies	-0.6	-3.2	-1.2
No external agriculture development + Constant public services	0	0.3	0.1
No external agriculture development + No Ejido	0	-0.2	-0.4
Constant public services + No ejido	-0.6	-3.1	-0.9
Without all the global drivers	13	21.5	14
Constant rainfall + No hurricanes	2.6	9.8	0.8
Constant rainfall + Constant market prices	10.3	15.2	13.9
Constant market prices + No hurricanes	-0.1	-2	-0.7
Without all the external drivers	-4.7	-12.5	5.4

Figure 10. Results of the experimental simulations. Effects of removing all the combinations by pairs into the groups of regional drivers and global drivers on the dynamics of the target variables: *population, total services indicator, and unemployment indicator.*



DISCUSSION AND CONCLUSIONS

We herein used the system dynamics model "SESSMO" to analyze the effects of environmental and socio-economic changes on global and regional scales on a small-scale agro-system in Baja California Sur (BCS, Mexico). The developed model helped to understand the trade-offs and synergies between the factors responsible for the decline of the Oasis of Comondú, whose population dropped 75% from 1940 to 2010.

SESSMO successfully simulated the historical behavior (1940-2010) of the main study system components (Tenza *et al*. 2017). Model testing showed the robustness of our model structure and the agreement between the simulated and the observed data (see Appendix B for details). According to our experimental simulations, the socio-economic and environmental external drivers that were linked to global processes (i.e. rainfall, hurricanes and market prices) had a stronger influence on the dynamics of this SES than the regional drivers (i.e. regional development policies: technical agriculture development in BCS, deviation of public investment to other urban centers, and delivery of common lands to landless people). However, the relative weight of the effects of all the external drivers on the decline (and depopulation) of this SES was lower than the endogenous drivers (e.g. local conditions, internal feedbacks). The analysis of the cross-scale interactions (i.e. from a global to a local scale) revealed some unexpected emerging properties that are typical of complex systems, such as the manifestation of trade-offs and synergies between the effects of the global and regional drivers.

Our model builds on a previous conceptualization process (Tenza *et al*. 2017), which included a qualitative model and a set of dynamical hypotheses. Our results agree with most of the hypotheses, especially as regards the consequences of the external drivers, but not as to the magnitude of these effects: i) development of more technical and modern agriculture in BCS, and the socio-political relocation of the oasis (in terms of reducing public investment) promoted the depopulation of the oasis; ii) delivery of common lands through the creation of the ejido Comondú halted the depopulation process and boosted the role of livestock activity; iii) both the creation of the ejido Comondú and dependence on livestock activity increased the vulnerability (and sensitivity) of this SES to extreme weather events (droughts and hurricanes); iv) market prices affected the profitability of productive activities and the local economy, which made livestock activity the most profitable.

Rainfall variability was the external driver that brought more uncertainty to the system, especially to local employment and population, whereas variability of market prices was the external driver that conferred more uncertainty to the local economy and the endogenous capability to invest in services. Tenza *et al*. (2017) hypothesized that regional development policies, especially external agricultural competition, would play the most important role in this SES' decline (i.e. by reversing the direction of positive feedbacks from growth to decline). However, our results evidence that the general role of regional development policies was limited. The external drivers linked to global processes, especially climatic ones, had more influence on the dynamics of this SES. More importantly, the reinforcing and compensating relations between the environmental and the socio-economic drivers warn about the vulnerability of this SES to the double climate change and globalization exposure (O´Brien and Leichenko 2000). The strong effect of the global drivers was compensated by the effect of the regional drivers. However, the relations between regional development policies were weaker. The most intense interactions occurred between the global drivers, with the synergic relation between rainfall variability and variability of market prices, and the synergy that arose between hurricanes and rainfall variability.

Despite the importance of the external drivers for understanding the dynamics of the system, and contrarily to what was expected, the effects of the external drivers (neither the regional nor the global drivers) did not explain the decline of the oasis of Comondú. It seemed that the endogenous conditions played a more important role in the origin of this SES' decline. As other authors have pointed out (Hanspach *et al*. 2014), local conditions strongly influence sustainability outcomes in spite of the effects of external drivers. The simulation results showed that, at the beginning of simulation, the indicators of unemployment, services and net economy had low levels when considering population size. In relation to the causes that triggered the decline of this SES, perhaps some endogenous factors that were important in the past were not captured by the dynamics which started in the 1940s. It has to be highlighted here that the time boundary in a simulation model should begin years before the problematic behavior starts (i.e. the decline process, which starts in the 1940s). However in our case, data availability determined the starting point of our study period in the 1940s. For example, at the beginning of the 20th century, the local production value would have been higher than our estimations with general market prices, and this value would have devaluated in the 1940s as the effects of modernity and capitalism grew. Another possibility is that inequality in land distribution played a more important role at the beginning of the 20th century by acting as a push factor for migration. Inequality in wealth distribution has been reported as a factor that could lead to the decline or even the collapse of SESs (Acosta-Naranjo 2002, Motesharrei *et al*. 2014). There is a 1938 record of the Comondú population requesting the distribution of more lands to landless people (Noriega *et al*. 2013), whereas our estimations indicated that inequality decreased considerably after the creation of the ejido in 1968 (see Appendix D for details). A brief review of data prior to the 1940s, done using historical archive records, suggests that the oasis of Comondú population suffered oscillations from its foundation in the 18th century to the 19th century, especially through epidemics, and it was not permanently established (Rodríguez-Tomp 2013). A qualitative change took place in the 19th century when productive lands were distributed. At that time, the population was settled and both the population and productivity of lands grew (Rodríguez-Tomp 2013). The collection of more data from historical archives, and the integration of land distribution, are factors in the dynamic simulation model that could shed some light on the main causes of this SES' decline in future research.

The results of this research confirm the importance of conducting quantitative models to understand the dynamics of complex systems, especially if the goal is to propose management measures or policy recommendations. In complex systems, the existence of feedbacks, delays, trade-offs and synergies challenge our understanding of the system's behavior, and can lead to misleading conclusions (Vennix 1996). The need to quantitatively model the dynamics of SESs is clear, but a frequent challenge is the availability of time data series. For our modelling purposes, the local knowledge and local ecological knowledge obtained by social research techniques during the previous conceptualization process, provided precise information on the data series of economic activities. Most of the data was used to define the model's parameters (Tenza *et al*. 2017). This source of information is rarely used in dynamic simulation models, probably because inter-disciplinary approaches and methodologies are lacking, and also because of the difficulties to obtain, manage and transform information from interviews into operative data in quantitative models. However as in other studies (Huntington 2000, Anadón *et al*. 2009, Pérez *et al*. 2012, 2016, Parry and Perez 2015), local knowledge and local ecological knowledge enhanced our knowledge of the system, and were critical for developing and validating our model. Notwithstanding, we recognize the model's inability to capture the large amount and richness of the qualitative information that we acquired from in-depth interviews and participants' observations because not all the information could be translated into quantitative data to be used by the model (Forrester 1992, Duffy *et al*. 2001, Luna-Reyes *et al*. 2003).

We herein studied the endogenous and exogenous factors of the decline in a small-scale agrosystem in Mexico to understand the complex interactions of environmental and socio-economic variables on different geographic scales. In summary, our findings show that the socio-economic/environmental changes interaction on global scales, along with the system's endogenous structure, are critical for the resilience of small-scale SESs. The complexity of these interactions hinders the adaptive capacity of small-scale agrosystems, and highlights the importance of integrating local ecological knowledge into quantitative simulation models to better understand the consequences of global changes. SESSMO can be used to support decision-making processes, and can help to identify the most effective management options for system resilience. Research into how endogenous factors model the consequences of climate change and current uncertainty about global markets is critical to improve the adaptive capacity of small-scale agrosystems and global food security.

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References

Abel, N., Cumming, D.H.M, Anderies, J.M. 2006. Collapse and reorganization in social-ecological systems: Questions, some ideas, and policy implications. *Ecology and Society* 11, #17.

Acosta-Naranjo, R. (2002). Los entramados de la diversidad. Antropología Social de la Dehesa. Colección raíces nº16, Diputación de Badajoz, Badajoz, Spain.

Allen, C.R., Angeler, D.G., Garmestani, A.S, Gunderson, L.H, Holling, C.S. 2014. Panarchy: Theory and Application. *Ecosystems* 17, 578–589.

Anadón, J.D., Giménez, A., Ballestar, R., Pérez, I. 2009. Evaluation of local ecological knowledge as a method for collecting extensive data on animal abundance. *Conservation Biology* 23, 617–625.

Andarzian, B., Bannayan, M., Steduto, P., Mazraeh, H., Barati, M.E., Barati, M.A., Rahnama, A., 2011. Validation and testing of the AquaCrop model under full and deficit irrigated wheat production in Iran. *Agricultural Water Management* 100, 1–8.

Ascough II, J.C., Maier, H.R., Ravalico, J.K., Strudley, M.W. 2008. Future research challenges for incorporation of uncertainty in environmental and ecological decision-making. *Ecological Modelling* 219, 383–399.

Balvanera, P., Daw, T.M., Gardner, T.A., Martín-López, B., Norström, A.V., Speranza, C.I., Spierenburg, M., Bennet, E.M., Farfan, M., Hamann, M., Kittinger, J.N., Luthe, T., Maas, M., Peterson, G.D., Perez-Vedin, G. 2017. Key features for more successful place-based sustainability research on social-ecological systems: a Programme on Ecosystem Change and Society (PECS) perspective. *Ecology and Society* 22, #14.

Banos-González, I., Martínez-Fernández, J., Esteve, M.A. 2015. Dynamic integration of sustainability indicators in insular socio-ecological systems. *Ecological Modelling* 306, 130–144.

Banos-González, I., Martínez-Fernández, J., Esteve, M.A. 2016. Using dynamic sustainability indicators to assess environmental policy measures in Biosphere Reserves. *Ecological indicators* 67, 565–576.

Banos-González, I., Terrer, C., Martínez-Fernández, J., Esteve-Selma, M.A., Carrascal, L.M. 2016. Dynamic Modelling of the potential habitat loss of endangered species: the case of the Canarian houbara bustard (Chlamydotis undulata fuerteventurae). *European Journal of Wildlife Research* 62, 263–275.

Barlas, Y. 1989. Multiple tests for validation of system dynamics type of simulation models. *European Journal of Operational Research* 42, 59–87.

Barlas, Y. 1996. Formal aspects of model validity and validation in system dynamics. *System Dynamics Review* 12, 183–210.

Baur, I. Rinder, C.R. 2015. Modeling and assessing scenarios of common property pastures management in Switzerland. *Ecological Economics* 119, 292–305.

Berkes, F, Colding, J., and Folke, C. (2003). Navigating social-ecological systems. Building Resilience for Complexity and Change. Cambridge University Press, Cambridge.

Bunce, M., Mee, L., Rodwell, L.D., Gibb, R. 2009. Collapse and recovery in a remote island – A tale of adaptive cycles or downward spirals? *Global Environmental Change* 19, 213–226.

Cariño, M. 2001. La oasisidad, núcleo de la cultura sudcaliforniana. *Gaceta Ecológica* 60, 57–69.

Cariño, M., Breceda, A., and Tenza, A. (2016). Los oasis: sistemas socioambientales tradicionales de la península de Baja California. In: Moreno-Calles, A.I., Casas, A., Toledo, V.M., and Vallejo-Ramos, M. (Eds.). Etnoagroforestería en México. Universidad Autónoma Nacional de México, Escuela Nacional de Estudios Superiores Unidad de Morelia, Instituto de Investigaciones en Ecosistemas y Sustentabilidad, Mexico City, pp. 149–169.

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., Spierenburg, M. 2012. Program on ecosystem change and society: an international research strategy for integrated social-ecological systems. *Current Opinion in Environmental Sustainability* 4, 134–138.

Ceriani, L., Verme, P. 2012. The origins of the Gini index: extracts from Viariabilità e Mutabilità (1912) by Corrado Gini. *Journal of Economic Inequality* 10, 421–443.

Challies, E., Newig, J., Lenschow, A. 2014. What role for social-ecological systems research in governing global teleconnections? *Global Environmental Change* 27, 32–40.

Collantes, F. 2007. The Decline of Agrarian Societies in the European Countryside: A case study of Spain in the Twentieth Century. *Agricultural History* 81, 76–97.

Collantes, F., Pinilla, V. 2004. Extreme Depopulation in the Spanish Rural Mountain Areas: A Case Study of Aragon in the Nineteenth and Twentieth Centuries. *Rural History* 15, 149–166.

Comisión Nacional de los Salarios Mínimos (CONASAMI). 2013. Salarios mínimos generales por áreas geográficas. Accessed 20 June 2017. URL: http://www.conasami.gob.mx/pdf/salario_minimo/sal_min_gral_area_geo.pdf

Conway, F.J. (2013). Desarticulación de la sociedad oasiana (1947–2010). In: Cariño, M., Breceda, A., Ortega, A., and Castorena, L. (Eds.). Evocando el edén. Conocimiento, valoración y problemática del Oasis de Los Comondú. Icaria editorial, Barcelona, pp. 317–338.

Davis, B., Stecklov, G., Winters, P. 2002. Domestic and international migration from rural Mexico: Disaggregating the effects of network structure and composition. *Population Studies* 56, 291–309.

Duffy, S.B., Corson, M.S., Grant, W.E. 2001. Simulating land-use decisions in the La Amistad Biosphere Reserve buffer zone in Costa Rica and Panama. *Ecological Modelling* 140, 9–29.

Eakin, H. 2005. Institutional Change, Climate Risk, and Rural Vulnerability: Cases from Central Mexico. *World Development* 33, 1923–1938.

Eakin, H., Winkels A., Sendzimir, J. 2009. Nested vulnerability: cross-scale linkages and vulnerability teleconnections in Mexican and Vietnamese coffee systems. *Environmental Science and Policy* 12, 398–412.

FAO. (2014). The State of Food and Agriculture: Innovation in family farming. FAO, Rome.

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

Ford A. 1990. Estimating the impact of efficiency standards on the uncertainty of the Northwest electric system. *Operations Research* 38, 580–597.

Forrester, J. W. (1973). World Dynamics. Pegasus Communications, Waltham, Massachusetts.

Forrester, J. W. 1958. Industrial Dynamics: A Major Breakthrough for Decision Makers. *Harvard Business Review* 36: 37–66.

Forrester, J.W. 1992. Policies, decisions and information sources for modeling. *European Journal of Operational Research* 59, 42–63.

Graham, A.K., Moore, J., Choi, C.Y. (2002). How robust are conclusions from a complex calibrated model, really? A project management model benchmark using fit-constrained Monte Carlo analysis. In: Proceedings of the XX System Dynamics Conference, System Dynamics Society, Palermo, Italy, 28 July–1 August.

Gunderson L.H., and Holling, C.S. (Eds.). (2002). Panarchy: understanding transformations in human and natural systems. Island Press, Washington DC.

Hanspach, J., Hartel, T., Milcu, A.I., Mikulcak, F., Dorresteijn, I., Loos, J., von Wehrden, H., Kuemmerle, T., Abson, D., Kovács-Hostyánszki, A., Báldi, A., Fischer, J. 2014. A holistic approach to studying social-ecological systems and its application to southern Transylvania. *Ecology and Society* 19, #32.

Holling, C.S. 1987. Simplifying the complex: the paradigms of ecological function and structure. *European Journal of Operational Research* 30, 139–146.

Holling, C.S. 2001. Understanding the complexity of economic, ecological, and social systems. *Ecosystems* 4, 390–405.

Huntington, H.P., 2000. Using traditional ecological knowledge in science: methods and applications. *Ecological Applications* 10, 1270–1274.

Instituto Nacional de Estadistica y Geografia (INEGI). (2009). Estadísticas Históricas de México. Vol. 1. Tomo II. Tema 17, precios, Mexico City, Mexico.

Instituto Nacional de Estadística y Geografía (INEGI). 2011. Marco Geoestadístico Nacional: Localidades geoestadísticas, archivo histórico. Accessed 20 June 2017. URL:
http://www.inegi.org.mx/geo/contenidos/geoestadistica/introduccion.aspx

Janssen, M.A., Anderies, J.M, Ostrom, E. 2007. Robustness of Social-Ecological Systems to Spatial and Temporal Variability. *Society and Natural Resources* 20, 1–16.
Jørgensen, S.E., and Bendoricchio. 2001. Fundamentals of Ecological Modelling. Elsevier Science, Oxford.

Jørgensen, S.E., Fath, B.D. (2011). Fundamentals of Ecological Modelling: Applications in Environmental Management and Research. Elsevier, Amsterdam.

Li, F.J., Dong, S.C., Li, F., 2012. A system dynamics model for analyzing the eco-agriculture system with policy recommendations. *Ecological Modelling* 227, 34–45.

Luna-Reyes, L.F., Andersen, D.L. 2003. Collecting and analyzing qualitative data for system dynamics: methods and models. *System Dynamics Review* 19, 271–296.

Luukkanen, J., Vehmas, J., Panula-Ontto, J., Allievi, F., Kaivo-Oja, J., Pasanen, T., Aufferman, B. 2012. Synergies or Trade-offs? A New Method to Quantify Synergy Between Different Dimensions of Sustainability. *Environmental Policy and Governance* 22, 337–349.

Martínez-Fernández, J., Esteve-Selma, M.A., Calvo-Sendín, J.F. 2000. Environmental and Socioeconomic Interactions in the Evolution of Traditional Irrigated Lands: A Dynamic System Model. *Human Ecology* 28, 279–299.

Meadows, D.H., Meadows, D.L., Randers, J., and Behrens III, W.W. (1972). The limits to growth. Universe Books, New York.

Mix, K., Lopes, V.L., Rast, W. 2015. A Systems Approach to Understanding the Evolution of the Agro-Social-Ecological System of the Upper Rio Grande-San Luis Valley, Colorado. *Water Resource Management* 29, 233–251.

Motesharrei, S., Rivas, J., Kalnay, E. 2014. Human and nature dynamics (HANDY): Modeling inequality and use of resources in the collapse or sustainability of societies. *Ecological Economics* 101, 90–102.

Nayak, P.K., Berkes, F. 2014. Linking global drivers with local and regional change: a social-ecological system approach in Chilika Lagoon, Bay of Bengal. *Regional Environmental Change* 14, 2067–2078.

National Oceanic and Atmospheric Administration (NOAA). Historical Hurricane Tracks. Accessed 20 June 2017. URL: https://coast.noaa.gov/hurricanes/

Noriega, J., Tenza, A., Castorena, L. (2013). El conflicto por la tenencia y uso de la tierra. In: Cariño, M., Breceda, A., Ortega, A., and Castorena, L. (Eds.). Evocando el edén. Conocimiento, valoración y problemática del Oasis de Los Comondú. Icaria editorial, Barcelona, pp. 439–454.

O´Brien, K.L, Leichenko, R.M. 2000. Double exposure: assessing the impacts of climate change within the context of economic globalization. *Global Environmental Change* 10, 221–232.

Oliva, R., 2003. Model calibration as a testing strategy for system dynamics models. *European Journal Operational Research* 151, 552–568.

Parry, L., Peres, C.A. 2015. Evaluating the use of local ecological knowledge to monitor hunted tropical-forest wildlife over large spatial scales. *Ecology and Society* 20, #15.

Pérez, I., Janssen, M.A., Anderies, J.M. 2016. Food security in the face of climate change: Adaptive capacity of small-scale social-ecological systems to environmental variability. *Global Environmental Change* 40, 82–91.

Pérez, I., Tenza, A., Anadón, J.D., Martínez-Fernández, J., Pedreño, A., Giménez, A. 2012. Exurban sprawl increases the extinction probability of a threatened tortoise due to pet collections. *Ecological Modelling* 245, 19–30.

Peterson, G.D., Cumming, G.S., and Carpenter, S.R. (Eds.). 2003. Scenario Planning: a Tool for Conservation in an Uncertain World. *Conservation Biology* 17, 358–366.

Pimentel, D., Acquay, H., Biltonen, M., Rice, P., Silva, M., Nelson, J., Lipner, V., Giordano, S., Horowitz, A., D´Amore, M. 1992. Environmental and Economic Costs of Pesticide Use. *BioScience* 42, 750–760.

Roberts, N., Andersen, D.F., Deal, R.M., Garet, M.S., and Shaffer, W.A. (1983). Introduction to computer simulation: the systems dynamics approach. Addison-Wesley, Reading, Massachusetts.

Rodríguez-Tomp, R.E. (2013). Comondú en el imaginario y la cultura misional. In: Cariño, M., Breceda, A., Ortega, A., and Castorena, L. (Eds.). Evocando el edén. Conocimiento, valoración y problemática del Oasis de Los Comondú. Icaria editorial, Barcelona, pp. 203–224.

Sancho & Cervera, J., Zavala, Z.F., Sánchez, V.M., Martínez, V.V. (1980). Monitoreo de sequías y heladas. Comisión del Plan Nacional Hidráulico, Dirección de inventarios de agua y suelo, Mexico City, pp. 14-16.

Sanga, G.J., Mungatana, E.D. 2016. Integrating ecology and economics in understanding land-use changes externalities internalization in water catchments. *Ecological Economics* 121, 28–39.

Saysel, A.K., Barlas, T., Yenigün, O. 2002. Environmental sustainability in an agricultural development project: a systems dynamics approach. *Journal of Environmental Management* 64, 247–260.

Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (SAGARPA). 2002. Manual de organización de la comisión técnico consultiva de coeficientes de agostadero. Accessed 20 June 2017. URL: http://www.sagarpa.gob.mx/desarrolloRural/Publicaciones/Lists/CursoTaller%20Desarrollo%20de%20capacidades%20orientadas%20a/Attachments/35/10.pdf

Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT). 2009. Compendio de Estadísticas Ambientales. Accesesed 20 June 2017. URL: http://www.semarnat.gob.mx/compendios-de-estadisticas-ambientales

Silva, J.A., Eriksen, S., Ombe, Z.A. 2010. Double exposure in Mozambique´s Limpopo River Basin. *The Geographical Journal* 176, 6–24.

Solecki, W., Oliveri, C., 2004. Downscaling climate change scenarios in an urban land use change model. *Journal of Environmental Management* 72, 105–115.

Secretaría de Promoción y Desarrollo Económico (SPyDE). (2002a). Estadísticas Históricas 1929–1956. Territorio Sur de Baja California. Gobierno del Estado de Baja California Sur, La Paz, Mexico.

Secretaría de Promoción y Desarrollo Económico (SPyDE). (2002b). Estadísticas Históricas 1956–1975. Territorio Sur de Baja California. Gobierno del Estado de Baja California Sur, La Paz, Mexico.

Secretaría de Promoción y Desarrollo Económico (SPyDE). (2003). Estadísticas Históricas 1975–1998. Estado de Baja California Sur. Gobierno del Estado de Baja California Sur, La Paz, Mexico.

Srivastava, P., Singh, R., Tripathi, R., Raghubanshi, A.S. 2016. An urgent need for sustainable thinking in agriculture – An Indian scenario. *Ecological Indicators* 67, 611–622.

Sterman, J., 1984. Appropriate summary statistics for evaluating the historical fit of system dynamics models. *Dynamica* 10, 51–66.

Sterman, J.D. (2000). Business Dynamics: Systems Thinking and Modeling for a Complex World. Irwin/McGraw-Hill, Boston.

Taylor, T.R., Ford, D.N., Ford, A. 2010. Improving model understanding using statistical screening. *System Dynamics Review* 26, 73–87.

Tenza, A., Pérez, I., Martínez-Fernández, J, Giménez, A. 2017. Understanding the decline and resilience loss of a long-lived social-ecological system: insights from system dynamics. *Ecology and Society* 22, #15.

Vennix, J.A.M. (1996). Group Model Building. Facilitating team learning using system dynamics. John Wiley & Sons, Chichester, United Kingdom.

Vidal-Legaz, B., Martínez-Fernández, J., Sánchez-Picón, A., Pugnaire, F. 2013. Trade-offs between maintenance of ecosystem services and socio-economic development in rural mountainous communities in southern Spain: a dynamic simulation approach. *Journal of Environmental Management* 131, 280–297.

Xiao-Qing, Z., Hui, R., Qi, Y., Chun-lan, H., Hong-hui, Y. 2012. Scenarios Simulation on Carrying Capacity of Water Resources in Kunming City. *Procedia Earth and Planetary Science* 5, 107–112.

Young, O.R., Berkhout, F., Gallopin, G., Janssen, M.A., Ostrom, E., Van der Leeuw, S. 2006. The globalization of socio-ecological systems: An agenda for scientific research. *Global Environmental Change* 16, 304–316.

Appendix A. Supplementary model description data

Table A.1. List and description of the parameters: socio-economic sector (rounded values).

Variable	Description	Value	Units	Source
pbr	Population birth rate	0.031	$year^{-1}$	Estimated from data of births and deaths of the local Civil Status Office and INEGI (2011)
pdr	Population death rate	0.0095	$year^{-1}$	Estimated from data of births and deaths of the local Civil Status Office and INEGI (2011)
mrr	Migration reference rate	0.02	$year^{-1}$	Estimated from data of births and deaths of the local Civil Status Office and INEGI (2011)
eap	Economically active population	0.34	dmnl	Census of housing and population (INEGI 2011)
iuiv	Initial unemployment indicator value	0.7471	dmnl	Calibrated with demand of employment and offer of local employment
ivpop	Initial value of population	1006	people	Census of housing and population (INEGI 2011)
iendcv	Initial endogenous capacity value	0.7288	dmnl	Estimated from interviews
itsiv	Initial total services indicator value	0.3123	dmnl	Estimated from interviews
depf	Depopulation factor	0.4802	dmnl	Automatic calibration
tproff	Total profitability factor	0.5035	dmnl	Automatic calibration
tddepef	Time delay on depopulation effects	6	year	Automatic calibration

Table A.2. List and description of the parameters: agriculture sector (rounded values).

Variable	Description	Value	Units	Source
arril	Abandonment reference rate of irrigated lands	0.0025	$year^{-1}$	Estimated from interviews and GIS data
eyil	Employment yield of irrigated lands	1	people ha^{-1}	Estimated from interviews
ieciv	Initial external competition indicator value	0.0175	dmnl	Calibrated with external agriculture development and irrigated lands
ivprofil	Initial value of profitability of irrigated land	660.5	pesos $year^{-1}$	Calibrated with total production and the net production value of irrigated lands
afecef	Amplification factor on external competition effects	2.894	dmnl	Automatic calibration
wfc1	Weighting factor for reference crop 1	0.42	dmnl	Estimated from interviews, GIS data and SPyDE (2002a, 2002b, 2003)
wfc2	Weighting factor for reference crop 2	0.37	dmnl	Estimated from interviews, GIS data and SPyDE (2002a, 2002b, 2003)
wfc3	Weighting factor for reference crop 3	0.21	dmnl	Estimated from interviews, GIS data and SPyDE (2002a, 2002b, 2003)
yil	Yield of irrigated land	2,663	kg ha^{-1} $year^{-1}$	Estimated from interviews, GIS data and SPyDE (2002a, 2002b, 2003)

Table A.3. List and description of the parameters: livestock sector (rounded values).

Variable	Description	Value	Units	Source
cla	Common land area	69,873	ha	National Agrarian Register Office (RAN)
ccrrv	Carrying capacity of rangelands (reference value)	29.6	ha au^{-1}	SEMARNAT (2009)
auc	Animal units per cattle	1	au $cattle^{-1}$	SAGARPA (2002)
aug	Animal units per goat	0.17	au $goat^{-1}$	SAGARPA (2002)
avrfll	Average rainfall	175	mm $year^{-1}$	Calibrated with rainfall data for the period 1939-2010 (National Water Comission Office, CONAGUA)
mxdi	Maximum intensity of droughts	-0.8	dmnl	Calibrated with rainfall data and Sancho and Cervera *et al*. (1980)
tdrfll	Time delay effects of rainfall on carrying capacity	1.7	year	Automatic calibration
sp	Saturation of ponds	52	ranches	Estimated from interviews and GIS data
nej	Number of ejidatarios	60	people	National Agrarian Register Office (RAN)
nrpp	Ranches per person	1	ranches $people^{-1}$	Estimated from interviews
gpr	Goats per ranch	133	goats $ranch^{-1}$	Estimated from interviews
igpr	Initial goats per ranch	50	goats $ranch^{-1}$	Estimated from interviews
ig	Initial goats	1,900	goats	Calibrated with initial goats per ranch and initial value of ranches
brg	Birth rate of goats	1	1/year	Estimated from interviews
gar	Goats per abandoned ranch	60	goats $ranch^{-1}$	Estimated from interviews

Table A.3. List and description of the parameters: livestock sector (continuation).

Variable	Description	Value	Units	Source
chprv	Cheese production per goat (reference value)	21	kg $goat^{-1}$	Estimated from interviews
srryg	Sale reference rate of young goats	0.5	1/year	Estimated from interviews
srrag	Sale reference rate of adult goats	0.05	1/year	Estimated from interviews
kgpg	Kilograms per goat sold	12	kg $goat^{-1}$	Estimated from interviews
prdg	Predation of goats	1,000	goats $year^{-1}$	Estimated from interviews
cbr	Cattle birth rate	0.57	1/Year	Estimated from interviews
src	Sale rate of cattle	0.19	1/Year	Estimated from interviews
kgpc	Kilograms per cattle sold	250	kg $cattle^{-1}$	Estimated from interviews
prdc	Predation of cattle	400	cattle $year^{-1}$	Estimated from interviews
cplu	Cattle per labour unit	100	cattle $people^{-1}$	Estimated from interviews
spc	Sustainable percentage of cattle	0.5703	dmnl	Automatic calibration
mxih	Maximum intensity of hurricanes	501.66	mm	Calibrated with maximum rainfall in 24 h (National Water Comission Office, CONAGUA) and NOAA (2011)

Table A.4. List and description of the external variables.

Variable	Explanation	Value	Units	Source
dcl	Delivery of common lands	1968	dmnl	National Agrarian Register office (RAN)
ead	External agriculture development	Time series data	ha	Urciaga (2008)
pubs	Public services	Time series data	dmnl	Estimated from interviews
gex	Goat expansion	1959	dmnl	Conway (2013)
ih	Intensity of hurricanes	Time series data	dmnl	National Water Comission Office (CONAGUA) and NOAA (2011)
mprc1	Market price of reference crop 1	Time series data	pesos kg^{-1}	SPyDE (2002a,b, 2003) and SIACON
mprc2	Market price of reference crop 2	Time series data	pesos kg^{-1}	SPyDE (2002a,b, 2003) and SIACON
mprc3	Market price of reference crop 3	Time series data	pesos kg^{-1}	SPyDE (2002a,b, 2003) and SIACON
mprch	Market price for goat cheese	Time series data	pesos kg^{-1}	SPyDE (2002a,b, 2003) and SIACON
mprg	Market price for goats	Time series data	pesos kg^{-1}	SPyDE (2002a,b, 2003) and SIACON
mprc	Market price of cattle	Time series data	pesos kg^{-1}	SPyDE (2002a,b, 2003) and SIACON
mw	Minimum wage	Time series data	pesos $people^{-1}$	INEGI (2009), CONASAMI (2013)
rfll	Annual rainfall	Time series data	mm $year^{-1}$	National Water Comission Office (CONAGUA)

† Market price series and minimum wage have been transformed from current prices into constant prices with 1975 as the reference year, using the Fisher index.
† † SIACON ("Agricultural Information System Consultation") is a data query tool of the "Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación" (SAGARPA). Data of production and market prices for the period 1980-2010 are available.

Table A.5. List and description of the model equations: socio-economic sector.

Variable / parameter	Description	Defining equation/value	Unit
Population	Human population of the oasis of Comondú	*+ b – d – m* [Initial value = 1006]	people
pb	Population births	*Population* × *pbr*	people $year^{-1}$
pbr	Population birth rate	0.031	$year^{-1}$
pd	Population deaths	*Population* × *pdr*	people $year^{-1}$
pdr	Population death rate	0.0095	1/year
pm	Population migration	*Population* × *pmr*	people $year^{-1}$
pmr	Migration rate	*mrr* × *efm*	$year^{-1}$
mrr	Migration reference rate	0.02	$year^{-1}$
efm	Effects on migration	*wf + ef*	dmnl
ef	Employment factor	*ui / iuiv*	dmnl
ui	Unemployment indicator	*If then else (de = 0 , 0 , (de - e)/de)*	dmnl
iuiv	Initial unemployment indicator value	0.7471	dmnl
de	Demand of employment	*Population* × *eap*	people
eap	Economically active population	0.34	dmnl
e	Offer of local employment	*eil + elv*	people
wf	Welfare factor	*1 + ((itsiv-tsi) / itsiv)*	dmnl
itsiv	Initial total services indicator value	0.3123	dmnl
tsi	Total services indicator	*(endcis* × *pubs) / 2*	dmnl
pubs	Public services	External data	dmnl
endcis	Endogenous capacity to invest in services	*iendcv* × *depefos* × *depf* × *tprofi* × *tproff*	dmnl
iendcv	Initial endogenous capacity value	0.7288	dmnl
depf	Depopulation factor	0.4802	dmnl
tproff	Total profitability factor	0.5035	dmnl
depefos	Depopulation effect on services	*DELAY1 (depi, tddepef)*	dmnl
tddepef	Time delay on depopulation effects	6	year
depi	Depopulation indicator	*Population / ivpop*	dmnl

Table A.5. List and description of the model equations: socio-economic sector (continuation).

Variable / parameter	Description	Defining equation/value	Unit
ivpop	Initial value of population	1006	people
tprofi	Total profitability indicator	*tnpv / ivtnpv*	dmnl
ivtnpv	Initial value of total net production value	760.84	pesos year^{-1}
tnpv	Total net production value	*npvil + ntpvlv*	pesos year^{-1}

Table A.6. List and description of the model equations: agriculture sector.

Variable / parameter	Description	Defining equation/value	Unit
Irrigated land	Irrigated land under production	*–ail* [Initial value = 78.9]	ha
ail	Abandonment of irrigated land	*(Irrigated land × aril) + (splil × utsplil)*	ha year^{-1}
aril	Abandonment rate of irrigated land	*arril × efail*	year^{-1}
arril	Abandonment reference rate of irrigated lands	0.0025	year^{-1}
efail	Effects on abandonment of irrigated land	*afecef × proflossi + defea*	dmnl
afecef	Amplification factor on external competition effects	2.894	dmnl
proflossi	Profitability loss of irrigated land indicator	*1+((ivprofil-profil) / ivprofil)*	dmnl
defea	Depopulation effects on economic activities	*1-depi*	dmnl
ivprofil	Initial value of profitability of irrigated land	660.5	pesos year^{-1}
profil	Profitability of irrigated land	*nvpvil × eci*	pesos year^{-1}

Table A.6. List and description of the model equations: agriculture sector (continuation).

Variable / parameter	Description	Defining equation/value	Unit
eci	External competition indicator	*(Irrigated land /ead) /ieciv*	dmnl
ieciv	Initial external competition indicator value	0.0175	dmnl
ead	External agriculture development	External data	ha
npvil	Net product value of irrigated land	*gpvil-pcil*	pesos $year^{-1}$
pcil	Production cost of irrigated land	*eil* × *mw* × *utpcil*	pesos $year^{-1}$
eil	Offer of local employment in irrigated land	*Irrigated land* × *eyil*	people
eyil	Employment yield irrigated lands	1	people ha^{-1}
mw	Minimum wage	External data	pesos $people^{-1}$
utpcil	Unit time for production costs of irrigated land	1	$year^{-1}$
gpvil	Gross production value of irrigated land	*tpil* × *(cv1 + cv2 + cv3)*	pesos $year^{-1}$
tpil	Total production of irrigated land	*Irrigated land* × *yil* × *utpil*	kg $year^{-1}$
utpil	Unit time for production in irrigated land	1	$year^{-1}$
cv1	Crop value 1	*wfc1* × *mprc1*	pesos kg^{-1}
wfc1	Weighting factor for reference crop 1	0.42	dmnl
mprc1	Market price of reference crop 1	External data	pesos kg^{-1}
cv2	Crop value 2	*wfc2* × *mprc2*	pesos kg-1
wf_{c2}	Weighting factor for reference crop 2	0.37	dmnl
mprc2	Market price of reference crop 2	External data	pesos kg^{-1}
cv3	Crop value 2	*wfc3* × *mprc3*	pesos kg-1
wf_{c3}	Weighting factor for reference crop 3	*0.21*	dmnl

Table A.6. List and description of the model equations: agriculture sector (continuation).

Variable / parameter	Description	Defining equation/value	Unit
mprc3	Market price of reference crop 2	External data	pesos kg^{-1}
lshil	Labour shortage in irrigated land	*If the else (de < eil, eil-de,0)*	people
splil	Surplus of irrigated land by labour shortage	*lshil / eyil*	ha
utsplil	Unit time for abandonment of excess irrigated land	1	$year^{-1}$

Table A.7. List and description of the model equations: Livestock sector.

Variable / parameter	Description	Defining equation/value	Unit
Ranches	Number of occupied ranches	*+ or – ar* [Initial value = 38]	ranches
or	Occupation of ranches	*(dcl × nej × nrpp) / utor*	ranches $year^{-1}$
utor	Unit time for occupation of ranches	1	$year^{-1}$
dcl	Delivery of common lands	*PULSE (1968, 1)*	dmnl
nej	Number of ejidatarios	60	people
nrpp	Number of ranches per people	1	ranches $people^{-1}$
ar	Abandonment of ranches	*(Ranches×dmar×utar)+(splr× utar)*	ranches $year^{-1}$
utar	Unit time for the abandonment of ranches	1	$year^{-1}$
splr	Surplus of ranches by labour shortage	*lshr × nrpp*	ranches
lshr	Labour shortage in ranches	*If then else (de < lnr, lnr-de, 0)*	people
lnr	Labour needed in ranches	*Ranches / nrpp*	peope
dmar	Decision making on abandonment of ranches	*defdmar × defea*	dmnl

Table A.7. List and description of the model equations: Livestock sector (continuation).

Variable / parameter	Description	Defining equation/value	Unit
defdmar	Drought effects on decision making of abandonment of ranches	*If then else (Ranches >= sp, MAX ((dder×(di/mxdi)),0),0)*	dmnl
sp	Saturation utility of temporary ponds	52	ranches
dder	Density dependence on ranches	*Ranches / snr*	dmnl
snr	Sustainable number of ranches	*sng / gpr*	ranches
gpr	Goats per ranch	133	goats $ranch^{-1}$
sng	Sustainable number of goats	*cla /(ccr × aug)*	goats
cla	Common land area	69,873	ha
aug	Animal units per goat	0.17	au $goat^{-1}$
ccr	Carrying capacity of rangelands	*ccrrv / rfllratio*	ha au^{-1}
ccrrv	Carrying capacity of rangelands (reference value)	29.6	ha au^{-1}
rfllratio	Rainfall ratio with average rainfall	*DELAY1(rfll/avrfll, tdrrfll)*	dmnl
rfll	Annual rainfall	External data	mm $year^{-1}$
avrfll	Average rainfall	175	mm $year^{-1}$
tdrrfll	Time delay effects of rainfall on carrying capacity	1.7	year
di	Drought indicator	*md / avrfll*	dmnl
md	Meteorological drought	*rfllac - avrfll*	mm $year^{-1}$
rfllac	Rainfall accumulated in 2 years	*rfll + rfll t-1*	mm $year^{-1}$
rfll t-1	Annual rainfall data with a 1-year delay	*Delay fixed (rfll, 1 , 141.8)*	mm $year^{-1}$
mxdi	Maximum intensity of droughts	-0.8	dmnl

Table A.7. List and description of the model equations: Livestock sector (continuation).

Variable / parameter	Description	Defining equation/value	Unit
Goats	Amount of goats	+ *pg* + *bg* - *sg* – *dg* [Initial value = 0]	goats
pg	Purchase of goats	*ig* × *gex* + *or* × *igpr*	goats $year^{-1}$
ig	Initial goats	1900	goats
gex	Goat expansion	*PULSE (1959,1)*	dmnl
igpr	Initial goats per ranch	50	goats $ranch^{-1}$
bg	Birth of goats	*Goats* × *brg* × *ddeg*	goats $year^{-1}$
brg	Birth rate of goats	1	$year^{-1}$
ddeg	Density-dependence effects on goats	*(sng - Goats) / (sng + Goats)*	dmnl
sg	Sale of goats	*syg* + *sag* + *gsar* + *splg*	goats $year^{-1}$
syg	Sale of young goats	*bg* × *sryg*	goats $year^{-1}$
sryg	Sale rate of young goats	*srryg* × *defsg*	$year^{-1}$
srryg	Sale reference rate of young goats	0.5	$year^{-1}$
defsg	Drought effects on sale of goats	*If then else (di < -0.2, 2 , 1)*	dmnl
sag	Sale of adult goats	*Goats* × *srag*	goats $year^{-1}$
srag	Sale rate of adult goats	*srrag* × *defsg*	$year^{-1}$
srrag	Sale reference rate of adult goats	0.05	$year^{-1}$
gsar	Goats sold by abandonment of ranches	*MIN (gar × ar , Goats × utgsar)*	goats $year^{-1}$
utgsar	Unit time for selling goats by abandonment of ranches	1	$year^{-1}$
gar	Goats per abandoned ranch	60	goats $ranch^{-1}$
splg	Surplus of goats by labour shortage	*MAX (Goats - sgl, 0)* × *utsplg*	goats $year^{-1}$
sgl	Sustainable number of goats by labour availability	*gpr* × *Ranches*	goats
utsplg	Unit time for selling surplus of goats	1	$year^{-1}$

Table A.7. List and description of the model equations: Livestock sector (continuation).

Variable / parameter	Description	Defining equation/value	Unit
dg	Death of goats	*Goats × utlvm × (efdlvm+efhlvm) + dgbp*	goats year^{-1}
utlvm	Unit time for livestock mortality	1	year^{-1}
efdlvm	Effects of droughts on livestock mortality	*MAX (di / mxdi , 0)*	dmnl
efhlvm	Effects of hurricanes on livestock mortality	*ih / mxih*	dmnl
ih	Intensity of hurricanes	External data	mm
mxih	Maximum intensity of hurricanes	501.66	mm
dgbp	Death of goats by predation	*If then else (di < -0.2, MIN(prdg, Goats × utprdg),0)*	goats year^{-1}
utprdg	Unit time for predation of goats	1	year^{-1}
prdg	Predation of goats	1000	goats year^{-1}
tchp	Total cheese production	*chppg × Goats × utchp*	kg year^{-1}
utchp	Unit time for cheese production	1	year^{-1}
chppg	Cheese production per goat	*chprv × defchp*	kg goat^{-1}
chprv	Cheese production per goat (reference value)	21	kg goat^{-1}
defchp	Drought effects on cheese production	*MIN ((mxdi-di) / mxdi, 1)*	dmnl
Cattle	Amount of cattle	*+ bc – dc - sc* [Initial value = 760]	cattle
bc	Birth of cattle	*Cattle × cbr × ddec*	cattle year^{-1}
cbr	Cattle birth rate	0.57	year^{-1}
ddec	Density-dependence effects on cattle	*spc + ((snc-Cattle) / (snc+Cattle))*	dmnl
spc	Sustainable percentage of cattle	0.5703	dmnl

Table A.7. List and description of the model equations: Livestock sector (continuation).

Variable / parameter	Description	Defining equation/value	Unit
snc	Sustainable amount of cattle	*ppa / (ccr × auc)*	cattle
ppa	Private property area	*106700 - STEP (69873, 1968)*	ha
auc	Animal units per cattle	1	au $cattle^{-1}$
dc	Death of cattle	*Cattle × utlvm × (defflvm+hefflvm) + dcbp*	cattle $year^{-1}$
dcbp	Death of cattle by predation	*If then else (di<-0.2, MIN (prdc, Cattle × utprdc),0)*	cattle $year^{-1}$
prdc	Predation of cattle	400	cattle $year^{-1}$
utprdc	Unit time for predation of cattle	1	$year^{-1}$
sc	Sale of cattle	*Cattle × src + splc × utsplc*	cattle $year^{-1}$
utsplc	Unit time for selling excess cattle	1	$year^{-1}$
src	Sale rate of cattle	0.19	$year^{-1}$
splc	Surplus of cattle by labour shortage	*lshc × cplu*	cattle
lshc	Labour shortage for cattle	*If then else (de < ec, ec-de, 0)*	people
cplu	Cattle per labour unit	100	cattle $people^{-1}$
npvlv	Net production value of livestock activity	*gpvlv - pclv*	pesos $year^{-1}$
gpvlv	Gross production value of livestock	*chv + gv + cv*	pesos $year^{-1}$
chv	Cheese value	*tchp × mprch*	pesos $year^{-1}$
mprch	Market price for goat cheese	External data	pesos kg^{-1}
gv	Goats value	*kggs × mprg*	pesos $year^{-1}$
kggs	Kilograms of goat sold	*sg × kgpg*	kg $year^{-1}$
kgpg	Kilograms per goat sold	12	kg $goat^{-1}$
mprg	Market price for goats	External data	pesos kg^{-1}
cv	Cattle value	*kgcs × mprc*	pesos $year^{-1}$
kgcs	Kilograms of cattle sold	*kgpc × sc*	kg $year^{-1}$
kgpc	Kilograms per cattle sold	250	kg $cattle^{-1}$
mprc	Market price of cattle	External data	pesos kg^{-1}

Table A.7. List and description of the model equations: Livestock sector (continuation).

Variable / parameter	Description	Defining equation/value	Unit
pclv	Production costs of livestock activity	$elv \times mw \times utpclv$	pesos $year^{-1}$
mw	Minimum wage	External data	pesos $year^{-1}$
utpclv	Unit time for production costs of livestock activity	1	$year^{-1}$
elv	Offer of local employment in livestock activity	$eg + ec$	people
eg	Offer of local employment with goats	$Goats / gplu$	people
gplu	Goats per labour unit	$gpr \times nrpp$	goats $people^{-1}$
ec	Offer of local employment with cattle	$Cattle / cplu$	people
cplu	Cattle per labour unit	100	cattle $people^{-1}$

Appendix B. Supplementary model testing data

B.1. Structural test

We checked consistency in model units to confirm the correctness of the model equations and the absence of conceptual errors. We extended the time horizon to 200 years to identify any possible anomalous behavior in the long term (e.g. negative values). Finally, we performed a set of extreme conditions tests to verify that the model behaves realistically beyond the conditions within which the model was calibrated (Li *et al*. 2012, Table B.1).

Table B.1. List and description of the extreme conditions tests (or reality checks).

Name	Condition	Expected behaviour
RC1	If *Population* = 0	Then *Irrigated land* = 0, *Ranches* = 0, *Goats* = 0, *Cattle* = 0, and *endogenous capacity to invest in services* = 0
RC2	If *migration rate* = *migration reference rate*	Then *Population* grows
RC3	Without *external agriculture development*	*Irrigated land* at the simulation end time is larger (compared with the results of the *Baserun*)
RC4	If *total profitability indicator* = 0	Then *endogenous capacity to invest in services* = 0
RC5	If *offer of local employment* = 0	Then *migration rate* increases and *Population* falls
RC6	If *total services indicator* = 0	Then *migration rate* increases and *Population* falls

B.2. Sensitivity analysis

We carried out a sensitivity analysis to assess the model's robustness (Graham *et al*. 2002). Each sensitivity analysis implied 200 model runs, where the parameter values were changed, and affected the behavior of the main variables. It represents an uncertainty analysis, where uncertainty comes from both lack of knowledge about the precise value of some parameters and the intrinsic real variability with other parameters (Ascough II *et al*. 2008). This analysis determines the model's robustness and, therefore, the reliability of the model's results.

A first local sensitivity analysis (one parameter at a time) was performed for all the model parameters with an extreme variation of 100% in their reference values (Ford 1990, Taylor *et al*. 2010). A sensitive index was calculated according to Jørgensen and and Fath (2011, Eq. (B.1)):

Eq. (B.1) $$S_i = \left(\frac{V_{max} - V_{min}}{V_{ref}}\right) \Big/ \left(\frac{P_{max} - P_{min}}{P_{ref}}\right) \times 100$$

where "S_i" is the sensitivity index, "V_{max}" and "V_{min}" are respectively the maximum and minimum values of the stock variable at the simulation end time in the sensitivity analysis (after 200 runs). "V_{ref}" represents the reference model value of the stock variable at the simulation end time (Baserun). "P_{max}" and "P_{min}" are respectively the maximum and minimum values of the parameter used in the sensitivity analysis, and "P_{ref}" is the reference model value of the parameter. This index is a measure of the relative variation of the variable of interest (each stock variable in our case) in relation to variation in one parameter.

Parameters were classified into the following categories: low sensitivity, when the sensitive index was lower than 10%; moderate sensitivity, between 10-49%; high sensitivity between 50-99%; very high sensitivity when the index was higher than or equaled 100%. The insensitive parameters (sensitive index equals 0%) for all the stock variables were removed from the model in a previous version, which improved the model's formulation.

We repeated a local sensitivity analysis with the parameters which showed moderate to very high sensitivity for at least one stock variable in the previous analysis, and after taking into account the expected range of variation for each parameter, based on available knowledge. With those parameters with no references for the expected variation range, variation of 50% compared to their reference values was applied (Table B.2). In this way, we avoided impossible conditions that could distort the model's behavior.

A general sensitivity analysis (multiple parameters at a time) was performed by Monte Carlo simulations. For this analysis, we chose the parameters with a higher sensitivity for each stock variable by considering their plausible range of variation. We calculated the variation coefficient for each variable and the range of variation within 95% confidence bounds according to Banos *et al*. (2016, Eq. (B.2)):

Eq. (B.2) $$\text{Variation coefficient} = \left(\frac{V_{max95} - V_{min95}}{V_{mean}}\right) \times 100$$

where "V_{max95}" and "V_{min95}" are respectively the maximum and minimum values of the variable of interest at the simulation end time using 95% confidence intervals, and "V_{mean}" is the mean value. The variation coefficient represents the relative variation of the variable of interest compared to its mean value using 95% confidence intervals. Table B.3 shows the main general sensitivity analysis results.

Table B.2. Results of the local sensitivity analysis using the expected ranges of variation for the parameters. The names of the parameters and stock variables, Population (Pop.) and Irrigated land (Irr. land) are abbreviated (see details of the parameters in Tables A.1 – A.3).

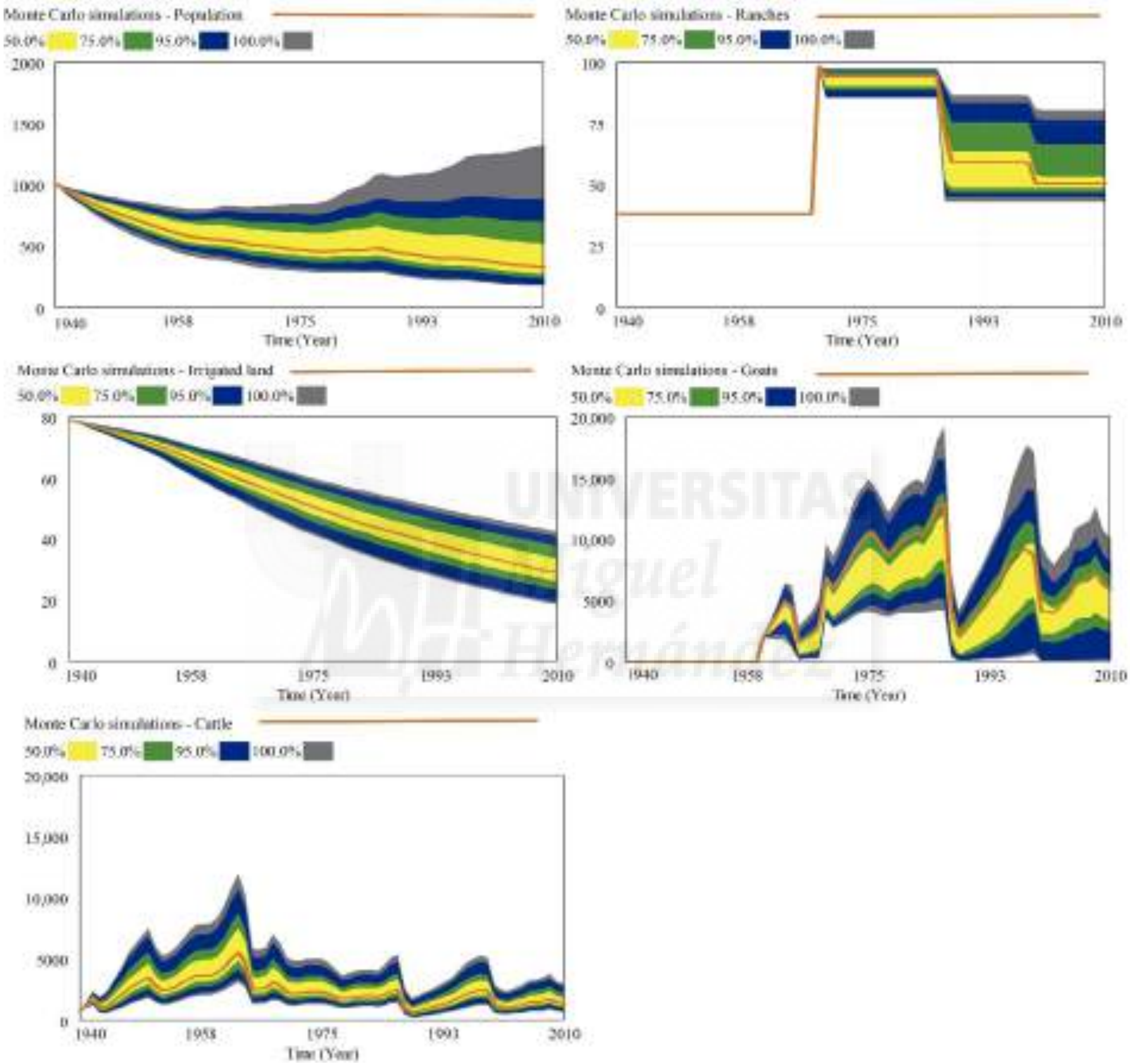
Parameters, reference values and plausible range of variation			Sensitivity index of the stock variables (%)				
Parameter	Model value	Range of variation	*Pop.*	*Irr. land*	*Ranches*	*Goats*	*Cattle*
aeff	2.89	2.17 – 3.62	21	95	4.4	2.6	0
arril	0.0025	0.002 – 0.003	22.6	104	4.7	2.8	0
auc	1	0.6 – 1.25	83.7	3.3	21.6	12	134.7
aug	0.17	0.12 – 0.26	50.6	1.2	28.5	66.5	0
cbr	0.57	0.4 – 0.7	48.1	2.3	8.4	5	125
ccrrv	29.6	29.6 – 55	45.5	1.6	17.4	48.5	54.5
chprv	21	16–26	34	0.9	8.4	5	0
cla	69873	52405–87341	56.8	1.4	29.7	65.8	0
depf	0.48	0.36 – 0.60	69	2.6	8.4	5	0
eap	0.34	0.24 – 0.42	120	4.2	22.8	13	0
eyil	1	1–2	31	3	6	3.5	0
gbr	1	0.61 – 1.16	54.9	1.3	7.7	112	0
gpr	133	30 – 400	6.5	0.2	25.9	25.2	0
ily	2663	1997–3329	21	16.6	8.4	5	0
kgpc	250	188–313	32	1.5	8.3	5	0
mrr	0.02	0.015 – 0.025	245	10.7	57.2	24.8	0
nrpp	1	1–2	14.8	0.3	12	6.7	0
pbr	0.031	0.028 – 0.034	171	7.4	20.9	12.6	0
pdr	0.0095	0.004 – 0.016	55.4	2.3	9.97	5.8	0
sp	52	26 – 52	3.6	0.07	16	10.6	0
spc	0.57	0.43 – 0.71	62	2.6	9	5.5	119.3
src	0.19	0.19 – 0.29	5.8	0.14	1.3	0.8	58.9
srrag	0.05	0.038–0.063	11.7	0.3	3	12	0
srryg	0.5	0. – 0.	43.8	1.5	11.4	199.5	0
tdrfll	1.7	1.3–2.1	5.7	0.1	11.2	7.8	0.6
tproff	0.50	0.38 – 0.63	69	2.6	8.4	5	0

Table B.3. Results of the general sensitivity analysis by means of Monte Carlo simulations.

Variable	Variation coefficient (%)	Mean value	95%CI
Population	163.5	433	± 354
Irrigated land	65.3	30.09	± 9.82
Ranches	77.8	54	± 21
Goats	149.9	4503	± 3375
Cattle	135.6	1550	± 1051

In relation to the obtained variation coefficients, the response of the stock variables to changes in their most sensitive parameters is classified as: low response (VC < 50%), moderate response (50% < VC < 100%), and high response (VC > 100%). Figure B.1 displays the graphical general sensitivity analysis results. Colored bands represent the different confidence intervals (50%, 75%, 95%, 100%) in relation to the percentage of simulations that obtain a certain result (values). This means that, for example, the colored band of the 50% confidence interval includes the results of 50% of the 200 simulations. In all cases, the general pattern of behavior is maintained.

Fig. B.1. The general sensitivity analysis results. The parameters included for the variable Population were: mrr, auc, eap, and pdr; for the variable Irrigated land: aeff and aril; for the variable Ranches: mrr and gpr; for the variable Goats: gpr, gbr, srryg, and aug; and for the variable Cattle: auc, spc, and cbr (see details of the parameters in Tables A.1 – A.3).



B.3. Behavioral tests

Comparing simulation results with the observed data is a measure of goodness of fit and, therefore, shows the model's ability to replicate real system behavior (Solecki and Oliveri 2004, Andarzian *et al*. 2011, Vidal-Legaz *et al*. 2013, Baur and Rinder 2015). This is a needed feature, but is not sufficient to determine confidence in the model, which also requires the suitability of the model structure and the robustness of the simulation results (Barlas 1996). Among the behavioral tests, we used Theil's U statistics, which is a set of statistical goodness-of-fit measures that are suitable for dynamic system models (Sterman 1984, Oliva 2003). The statistics tests included a correlation coefficient (R2) between the simulated and the observed data, and the computation of the mean absolute percentage error (MAPE, Eq. (B.3)), the mean square error (MSE), and the root of the mean square error (RMSE). The MSE (Eq. (B.4)) is decomposed into three factors: i) U^M (Eq. (B.5)) that represents the fraction of the mean quadratic error attributed to bias (unequal means); ii) U^S (Eq. (B.6)) that indicates the differences between the variances caused by amplitude or noise; iii) U^C (Eq. (B.7)) that is the unequal covariance, associated with the point-to-point differences between the simulated and the observed data (Baur and Rinder 2015). To Theil's statistics, we added the computation of the normalized root mean square error (NRMSE, Eq. (B.8)) proposed by Jamieson *et al*. (1991), which serves as an indicator of the difference between the simulated and the observed data (Andarzian *et al*. 2011). Simulation is considered excellent with an NRMSE under 10%, good between 10% and 20%, fair if it is higher than 20, but less than 30%, and poor if it is higher than 30% (Andarzian *et al*. 2011).

Eq. (B.3) $$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{S_t - A_t}{A_t}\right|$$

Eq. (B.4) $$MSE = \frac{1}{n}\sum_{t=1}^{n}(S_t - A_t)^2$$

Eq. (B.5) $$U^M = \frac{(\bar{S} - \bar{A})^2}{MSE}$$

Eq. (B.6) $$U^S = \frac{(S_S - A_A)^2}{MSE}$$

Eq. (B.7) $$U^C = \frac{2 \times (1 - r) \times S_S \times A_A}{MSE}$$

Eq. (B.8) $$NRMSE = \frac{1}{\bar{A}}\sqrt{\frac{1}{n}\sum_{t=1}^{n}(S_t - A_t)^2}$$

where S_t and A_t are the simulated and the observed (actual) data at time t, respectively; $\bar{S}$ and $\bar{A}$ are the mean values of the simulated and the observed data, respectively; S_S and A_A are the standard deviation of the simulated and the observed data, respectively; r is the correlation coefficient between both series (simulated and observed data); n is the number of observations. Table B.4 summarizes the main results of the behavioral tests.

Table B.4. Results of the statistic assessment of goodness of fit.

Variables	n	R^2	MAPE (%)	U^M(%)	U^S(%)	U^C(%)	NRMSE (%)
Population	10	0.93	9.2	3.6	16	80	11.5
Irrigated lands	8	0.97	9.0	7	38	55	7.8
Ranches	5	0.99	0.8	20	76	4	3.4
Goats	5	0.91	12.1	36	1	63	21.3
Cattle	3	0.99	0.3	0.2	69	31	0.3
Demand of employment	4	0.64	10.5	33.3	13.7	53	13.7
Population births	33	0.04	27.3	34.7	14.4	50.9	35.4
Population deaths	33	0.33	54.4	0.2	62.5	37.3	50.6

The statistical assessment of goodness of fit generally showed a good agreement between the simulated and the available observed data for the main model variables. However, the excellent fit for some variables should be interpreted with caution because data are scarce.

The correlation coefficient (R^2) was higher than 90% for all the stock variables. Demand of employment, and population births and deaths, displayed a lower correlation. The mean absolute percentage error (MAPE) exhibited low values for the stock variables and demand of employment, whereas population births and deaths obtained higher values. The decomposition of the mean square error revealed that, for most variables, the error concentrates in the incomplete covariance between the simulated and the observed data (U^C). The differences between variances (U^S) explained a higher percentage of the error in ranches, cattle and population deaths. In all cases, the smallest part of the error was due to bias. The computation of the normalized root mean square error (NRMSE) displayed very low values for irrigated land, ranches and cattle. The error (below 15%) was also low for population and demand of employment. Goats obtained a moderate error, which exceeded 20%. However, the fit of the simulated data to the historical data for population births and deaths once again showed the highest percentage of error, and exceeded 30% in both cases.

Appendix C. Supplementary data of the experimental simulations

Table C.1. List and description of the experimental simulations.

Simulation name	Description
No external agriculture development	Simulation without the effects of external competition
Constant public services	Simulation without the effects of socio-political relocation in public investment terms
No Ejido	Simulation without the delivery of common lands
No external agriculture development + Constant public services	Simulation without external competition and socio-political relocation
No external agriculture development + No Ejido	Simulation without external competition and the delivery of common lands
Constant public services + No ejido	Simulation without socio-political relocation and the delivery of common lands
Without all the regional drivers	Simulation without the effects of all the regional development policies
Constant rainfall	Simulation without variability of rainfall
No hurricanes	Simulation without tropical cyclones
Constant market prices	Simulation without variability of market prices
Constant rainfall + No hurricanes	Simulation without variability of rainfall and the occurrence of tropical cyclones
Constant rainfall + Constant market prices	Simulation without variability of rainfall and variability of market prices
Constant market prices + No hurricanes	Simulation without variability of market prices and the occurrence of tropical cyclones
Without all the global drivers	Simulation without the effects of all the external drivers related with global processes
Without all the external drivers	Simulation without the effects of all the external conditions

C.1 Equation used to obtain the variation coefficient in the experimental simulations

Eq. (C.1) $$\text{Variation coefficient} = \left(\frac{V_{exp} - V_{Baserun}}{V_{Baserun}}\right) \times 100$$

This coefficient measures the relative variation of the results of experimental simulations compared to the *Baserun* simulation results for the target variables, where “V_{exp}” is the target variable value at the experimental simulation end time, and “$V_{Baserun}$” is the target variable value at the *Baserun* simulation end time.

Appendix D. Supplementary data used to estimate the Gini coefficient

The Gini coefficient is a measure of the inequality of the wealth distribution in a given population, as proposed by Corrado Gini in 1912 (Ceriani and Verme 2012). The equations used in our estimation are as follows:

Eq. (D.1) $GC = \sum (pi - qi) / \sum (pi)$

Eq. (D.2) $pi = \sum ni/n$

Eq. (D.3) $qi = \sum (Xi \times ni)/Xn \times nn$

where X_i represents the resources or wealth (e.g. incomes, land) by classes, n_i is the population (e.g. potential landowners) in each class (frequencies), n is the total population, p_i represents the cumulative relative frequency of the population, and qi is the cumulative product between wealth and the population. The Gini coefficient value ranges from 0 to 1, where 1 represents perfect inequality, whereas 0 represents perfect equality.

We calculated the Gini coefficient for two different periods, before the creation of the ejido Comondú in 1940 (our initial study period time), and after the creation of the ejido in 2010 (our study period end time). To calculate the distribution and accumulation of land in the oasis, we considered the economically active population, which represents 34% of the entire population. With this selection, we ruled out the percentage of the population who are not potential landowners (e.g. children, the elderly). In this estimation, we took into account the larger land properties of the oasis (i.e. private properties and common land used for ranching). We excluded the smallholdings used to work irrigated land, whose size ranges from 0.3-2.4 ha. Tables D.1–D.2 display the main data used to calculate this coefficient.

Our estimations indicated that the Gini coefficient changed from 0.65 (before the creation of the ejido) to 0.28 (after the creation of the ejido).

Table D.1. The distribution of land in the oasis of Comondú before the creation of the ejido (1940). Property size is classified into classes.

Properties size (ha)	Population (people)
0	315
500	3
600	2
700	1
1000	3
1500	1
2000	2
3500	1
4000	2
5000	1
8000	1

Table D.2. The distribution of land in the oasis of Comondú after the creation of the ejido (2010). Property size is classified into classes.

Properties size (ha)	Population (people)
0	31
500	3
600	2
700	1
1000	63
1500	1
2000	2
3500	1
4000	2
5000	1
8000	1

CAPÍTULO 3

*Chinchorro de cabras (fotografía de Andrés Giménez Casalduero)

Can local policies reverse the decline process of small social-ecological systems caused by global change?

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Abstract

Managing the resilience of small-scale social-ecological systems in desirable and sustainable dynamics is crucial for global sustainability. However, these systems are now threatened by effects of global change. We presented an advanced step of long-term research of a small-scale agrosystem in Mexico, which has undergone a dramatic transition from growth to decline in the past century, influenced by environmental and socio-economic changes on global and regional scales. Using a dynamic simulation model and the sensitivity analysis tool, we identified the main sensitive points to intervene in this system. We evaluated the effects of these interventions on local dynamics by simulating management scenarios. We compared the results with the policy options and management measures proposed by stakeholders. Our results, along with the future examination of the complete set of management measures proposed by stakeholders, could support decision-making processes to guide this SES toward a sustainable path.

Keywords: System dynamics; Leverage points; Stakeholders; Sustainability; Place-based research; Arid environment

INTRODUCTION

The dynamics of our global social-ecological system (SES) is unsustainable. Sixty percent of the world´s ecosystem services have deteriorated as a result of our social metabolism (Millennium Ecosystem Assessment 2005, González de Molina and Toledo 2014). Small-scale, long-lived SESs persist as examples of alternative livelihoods, characterized by resilient management models of natural resources that support global food security and encourage institutional diversity (Janssen *et al*. 2007, FAO 2014). However, these systems are now threatened by global change (Young *et al*. 2006). They are exposed, as never before in their history, to new perturbations, social-economic changes, increased variability of natural resources, and extreme weather events, which all challenge their adaptive capacity (Young *et al*. 2006, Janssen *et al*. 2007). Understanding the structure and dynamics of these SESs can support decision-making processes to manage their resilience in the face of uncertain climatic and socio-economic future scenarios.

In the last decade, a new perspective has emerged from the core of the sustainability science. For global sustainability, the stewardship of SESs in sustainable dynamics is crucial. Problem- or solution-oriented processes, and place-based, long-term, social-ecological research, are needed to manage the resilience of these systems in their desirable states (Carpenter *et al*. 2012, Balvanera *et al*. 2017). However, the success of these studies is challenged by not only the complexity of these systems, but also by the need for more integrative approaches, including inter-multidisciplinary collaboration and the participation of stakeholders, which exceed conventional research activities (Balvanera *et al*. 2017).

We present herein one of the advanced steps of long-term research about a small-scale, long-lived, agro-system in Baja California Sur (BCS, Mexico), which has undergone a dramatic transition from growth to decline in the past century, influenced by environmental and socio-economic changes on global and regional scales. As in many other rural areas of the world, it has witnessed a serious depopulation process that threatens their long-term existence. Using the System Dynamics approach, in previous steps we conducted interdisciplinary research to identify the main structural causes of the decline in this SES (Tenza *et al*. 2017). We developed and validated a dynamic simulation model with a vast amount of data that stem from local knowledge and local ecological knowledge to analyze the causes of this decline in SES, and to measure the relative weight of external drivers in this process (Tenza *et al*., submitted).

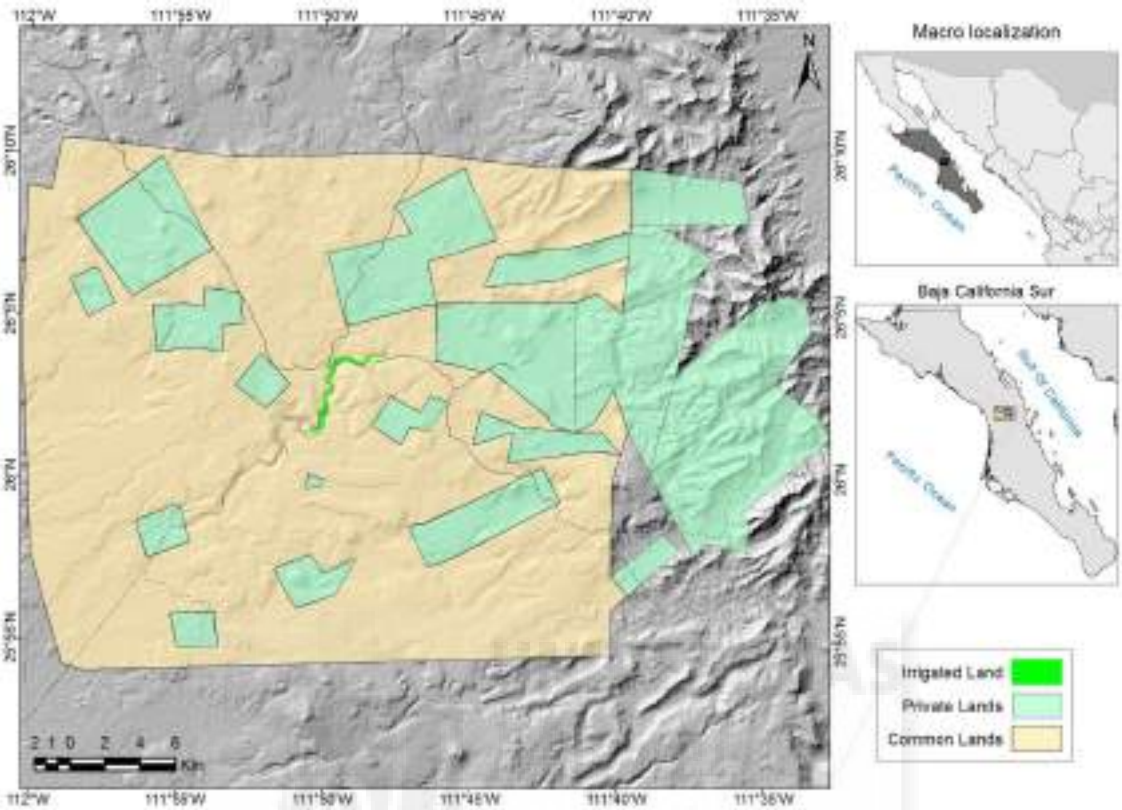
We herein used our dynamic simulation model and the sensitivity analysis tool to identify the most sensitive places or leverage points to intervene in this SES (i.e., parameters whose changes can trigger qualitative changes in the system dynamics with less effort). We compared the results with the policy options and management measures proposed by three groups of stakeholders (i.e., local actors, the regional BCS government, and the academia). By taking into account the historical trend of the SES over the last 70 years, and the influence of regional and global drivers, we explored the following issues: can local policy options designed to act on these potential leverage points reverse the current trend toward collapse?; do stakeholders' proposals converge on these sensitive points?; which group of stakeholders is closer to these leverage points?; what are the differences in priorities among stakeholders? Our results can support future decision-making processes to encourage the sustainability of this SES.

METHODS

Study system and problematic behavior

The oasis of Comondú in BCS is a long-lived social-ecological system that has played an important role in the economy and culture of the region (Cariño *et al*. 2013). It is located in the municipality of Comondú, in the Sierra de La Giganta mountain range (WebFigure 1). Surrounded by an arid environment, availability of the water that emerges from natural springs has historically supported an irrigated agriculture, complemented by extensive livestock farming. The study area comprises 107,080 ha, 80 ha of which have been historically used to irrigated agriculture, and the remainder devoted to livestock activity (common lands and private properties). This SES has lived a dramatic transition from growth to decline in the first half of the twentieth century, when the population dropped from 1,006 inhabitants in 1940 to 257 in 2010 (a reduction of 74.5%). The local institutions that manage natural resources, local practices and local ecological knowledge are disappearing (Cariño *et al*. 2013, Tenza *et al*. 2017). The interplay between local conditions (i.e., local employment and economy and land distribution) and the effects of regional and global drivers have encouraged the depopulation process (Tenza *et al*., submitted). The main regional drivers have been regional development policies that have included: i) modernization and expansion of technical agriculture in BCS; ii) deviation of public investment to other urban areas and coastal tourism centers; iii) changes in property rights by delivering common lands to landless people. The global drivers that have historically affected this SES are: i) rainfall; ii) hurricanes; iii) the market prices of agricultural and livestock products.

WebFigure 1. Map of the study area in Baja California Sur (Mexico) with details of the irrigated land, private and common lands of the oasis of Comondú.

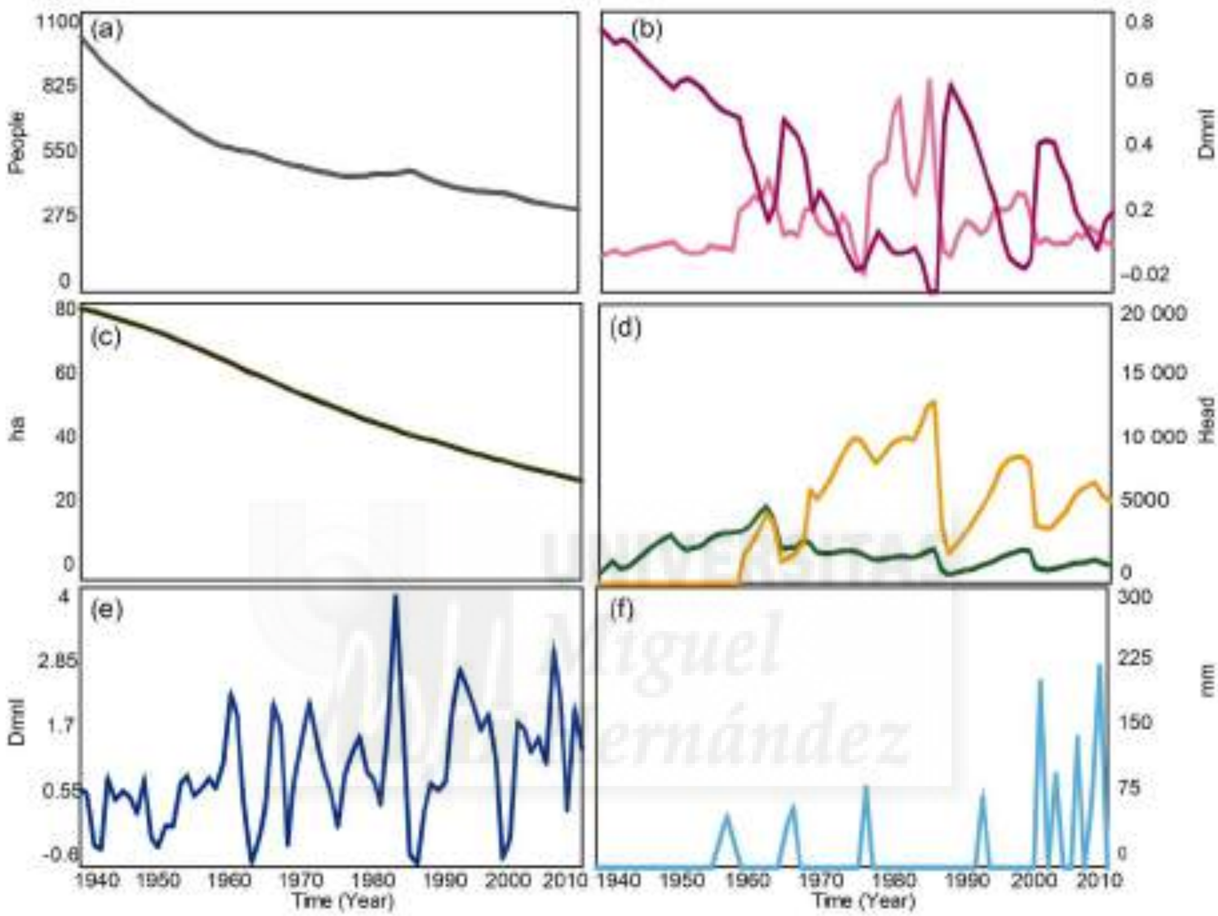


Model description

This study builds on a previous dynamic simulation model called "SESSMO" (from the "Social-Ecological System Sustainability Model"), which simulated the historical behavior of the main SES components for the 1940-2010 period (Tenza *et al.*, submitted, WebFigure 2). Our model relies on the System Dynamics approach, where the complexity of the system emerges from non linear relationships, feedbacks and information or material delays (Vennix 1996). The model was developed with the Vensim DSS 6.4c software (Ventana Systems). By means of structural and behavioral tests (Barlas 1996), we formally tested our model (Tenza *et al.*, Submitted).

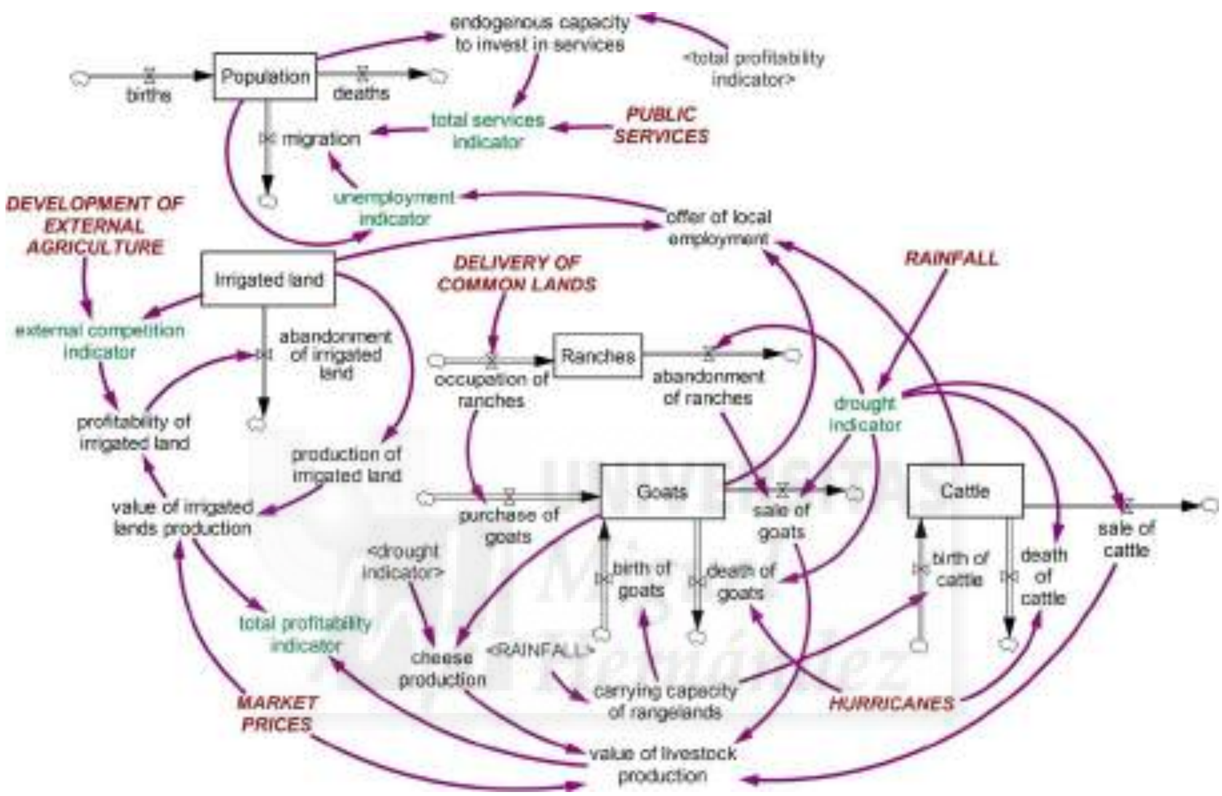
Our model has five stock variables that represent the state of the system: human population, irrigated land with production, occupied ranches, amount of cattle, and amount of goats (WebFigure 3). The dynamics of productive activities (i.e., agriculture and livestock farming) determines the offer of local employment and the economy of the oasis. Local employment and availability of services, as relevant indicators of welfare in the oasis, define the migration

WebFigure 2. The main simulation results during the historical period (1940-2010) of the following variables: (a) *population*; (b) *unemployment indicator* (violet line) and *total services indicator* (pink line); (c) *irrigated land*; (d) *cattle* (green line) *and goats* (yellow line); (e) *drought indicator*; and (f) *hurricanes*.



dynamics. Availability of services depends on local economy and public investment. We included the effects of the main external drivers (WebFigure 3). External agriculture development and market prices affect the profitability of productive activities. Public services reproduce loss of public services during the simulation period. Delivery of common lands increases the number of occupied ranches. Rainfall affects the carrying capacity of rangelands and livestock stocks because of drought periods (which increase the sale and death of animals). Hurricanes increase livestock mortality.

WebFigure 3. Simplified flow chart of SESSMO (Social-Ecological System Sustainability Model). Stock variables are shown in boxes. Pipelines are the input and output flow variables. External drivers are marked in italics and capital letters. Model indicators are depicted in green. The variables between the "lower than/higher than" symbols represent the variables located in the distant places of the same diagram.



Identification and analysis of the potential leverage points: simulation approach

The sensitivity analysis serves to identify the most sensitive parameters in a model. The sensitivity index of each parameter measures the relative variation of the target variables in relation to the variation of this parameter (Jørgensen and Fath 2011). Sensitivity ranges from low (<10%) to very high sensitivity (>100%). We used a local sensitivity analysis (i.e., modification of one parameter at a time) to identify the key parameters that could act as leverage points (WebTable 1, Meadows 1999, Turner *et al.* 2016). Leverage points, which can range from changes in parameters to changes in paradigms, feedbacks or time delays, are the best places to intervene in a system by management measures (Meadows 1999, Abson *et al.* 2017).

Of all the analyzed parameters (WebTable 1), we selected the five parameters of moderate to high sensitivity (following the classification of Jørgensen and Fath 2011), which are potentially modifiable by the management measures: i) yield of irrigated land; ii) weight of cattle for sale; iii) cheese production per goat; iv) cattle birth rate; v) birth rate of goats. To evaluate their potential effects, we aggregated the interventions into three groups according to productive sectors: i) improvement of agricultural yield; ii) improvement of goat yields; iii) improvement of cattle yields. The improvement of these parameters was based on the realistic changes made in similar productive systems with technical assistance and technology packages (WebTable 2). We simulated eight alternative scenarios for the 2010-2050 period, including the "business as usual scenario" (BAU scenario), which implied no changes in parameters, three scenarios with changes in each sector separately, three scenarios with combinations of sectors by pairs, and a scenario with changes in all the sectors at a time. All the interventions are implemented, starting in 2018. All the scenarios used an extension of the historical trends of external drivers (i.e., rainfall, hurricanes, market prices). We compared the simulation results of each scenario with the BAU scenario as a reference. Comparisons focused on the target variables: population, total services indicator and unemployment indicator, which are the most directly linked to the decline of this SES.

Identification of stakeholders' management proposals

During the 2014-2016 period, we extensively collected the management measures proposed by stakeholders, constituted by local actors (i.e., local inhabitants of the oasis), the regional BCS government, and the academia (i.e., a research team that made up RIDISOS ("Interdisciplinary Network for Integral and Sustainable Development of the Oases of Baja California Sur"). We reviewed in-depth interviews with local actors, which had been conducted in previous fieldwork (Tenza *et al*. 2017). We carried out a participatory workshop in December 2015, where local actors identified the main problems of the oasis, defined the future desired state, and proposed management measures to achieve this future. We reviewed the strategic plans of the regional BCS government and the RIDISOS publications (Cariño *et al*. 2013, Gámez 2013). We collected 102 observations, which were grouped by affinity or matches in 17 general management measures. These management measures were classified by sectors: i) agriculture; ii) livestock; iii) services; iv) tourism.

Ordering the observations by management measures and sectors allowed us to compare the priorities between local actors and the proximity or distance of such measures to the system's potential leverage points.

WebTable 1. Results of the local sensitivity analysis using the expected ranges of variation for each parameter. Parameters are classified into the following categories: low sensitivity, when the sensitive index was lower than 10%; moderate sensitivity, between 10-49%; high sensitivity, between 50-99%; very high sensitivity, when the index was higher than or equaled 100% (Jørgensen and Fath 2011). The parameters easily modifiable by interventions are indicated by asterisks. The sale rates of young goats and cattle are related to their birth rates. The intervention in birth rates affects directly these sale rates. We ruled out the sale rate of adult goats as a potential intervention point because it is a local marginal strategy to cope with drought periods.

Parameter (Units)	Model value	Range of variation	Units	Population sensitivity index (%)
Amplification factor on external competition effects	2.89	2.17 – 3.62	Dmnl	21
Abandonment reference rate of irrigated lands	0.0025	0.002 – 0.003	year^{-1}	22.6
Animal units per cattle	1	0.6 – 1.25	au cattle^{-1}	83.7
Animal units per goat	0.17	0.12 – 0.26	au goat^{-1}	50.6
Cattle birth rate*	0.57	0.4 – 0.7	year^{-1}	48.1
Carrying capacity of rangelands	29.6	29.6 – 55	ha au^{-1}	45.5
Cheese production per goat*	21	16–26	kg goat^{-1}	34
Common land area	69873	52405–87341	ha	56.8
Depopulation factor	0.48	0.36 – 0.60	Dmnl	69
Economically active population	0.34	0.24 – 0.42	Dmnl	120
Employment yield of irrigated lands	1	1–2	people ha^{-1}	31
Birth rate of goats*	1	0.61 – 1.16	year^{-1}	54.9
Goats per ranch*	133	30 – 400	goats ranch^{-1}	6.5
Yield of irrigated land*	2663	1997–3329	kg ha^{-1} year^{-1}	21
Weight of cattle for sale*	250	188–313	kg cattle^{-1}	32
Migration reference rate	0.02	0.015 – 0.025	year^{-1}	245
Ranches per person	1	1–2	ranches people^{-1}	14.8
Population birth rate	0.031	0.028 – 0.034	year^{-1}	171
Population death rate	0.0095	0.004 – 0.016	year^{-1}	55.4
Saturation of ponds	52	26 – 52	ranches	3.6
Sustainable percentage of cattle	0.57	0.43 – 0.71	dmnl	62
Sale rate of cattle*	0.19	0.19 – 0.29	year^{-1}	5.8
Sale reference rate of adult goats*	0.05	0.038–0.063	year^{-1}	11.7
Sale reference rate of young goats*	0.5	0.38 – 0.63	year^{-1}	43.8
Time delay effects of rainfall on carrying capacity	1.7	1.3–2.1	year	5.7
Total profitability factor	0.50	0.38 – 0.63	Dmnl	69

WebTable 2. Changes in parameters. Improvement in the livestock yield parameters (goats and cattle) would give rise to increases from 6.5% to 35% in the reference values. This improvement is feasible with the technical assistance and technology packages that focus on livestock health, livestock management and reproduction-genetics issues (Cepeda and Angulo 2013). Improvement in the agriculture yield would mean an increase of 25% in the reference value, which is a conservative value if we consider that multiple crops systems with agro-ecological management in Latin America could have more advantageous yields from 20% to 60% (Altieri 1999).

Parameter	Reference value	Improved value	Units
Yield of irrigated land	2663	3329	kg ha^{-1}
Weight of cattle for sale	250	315	kg $cattle^{-1}$
Cheese production per goat	21	22.4	kg $goat^{-1}$
Cattle birth rate	0.57	0.644	$year^{-1}$
Goats birth rate	1	1.35	$year^{-1}$

RESULTS

Simulation results of scenarios

Figure 1 displays the behavior of the target variables in the management scenarios based on leverage points. The improvement in production yields slightly enhanced the local conditions, especially the local employment offer. Population decline was decelerated under some scenarios, even reversed at the simulation end time. In the BAU scenario, population declines 25.15% during the simulation period. The improvement in goats yield influenced heavily the system dynamics, followed by the improvement in cattle yield. The improvement in agriculture yield had the least impact. Table 1 shows the variation coefficients of the alternative management scenarios in relation to the BAU scenario.

By pairs, the improvement of livestock yield (goats and cattle together) had the strongest impact, where the population was 11.5% higher than in the BAU scenario. The best results were achieved through the improvement in all the productive sectors (agriculture and livestock together), where the population was 12.3% higher than in the BAU scenario. In this scenario, the population even increased by 4.2% in the last decade of the simulation (Figure 1).

Figure 1. Simulation results of the management scenarios on the target variables: (a) *population*, (b) *total services indicator*, and (c) *unemployment indicator*. We decided to display the main simulations because there is some visual overlapping between the results of changing each productive sector separately and changing productive sectors by pairs (see Table 2 for details).

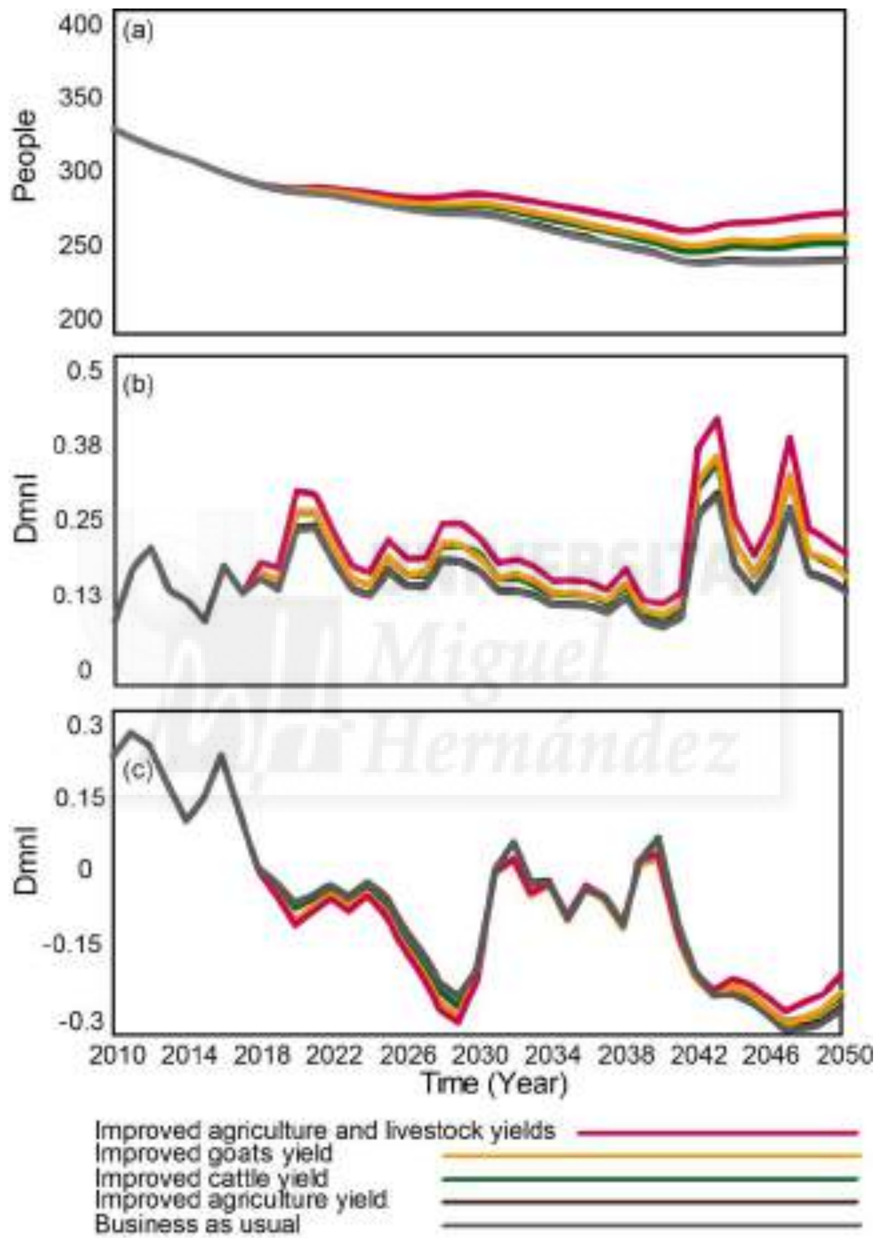


Table 1. Variation coefficients of the scenarios expressed as a percentage. For the comparison between the alternative management scenarios and the business as usual scenario (*BAU-Scenario*), we focused on the value of *population* at the simulation end time (t=2050) because it is a stock variable (i.e. a cumulative variable). For indicators total services and unemployment, we focused on the mean value of each simulation since it better represents the general trend.

Scenario	Population (End time) (%)	Total services indicator (Mean value) (%)	Unemployment indicator (Mean value) (%)
Improved agriculture yield	0.4	1.5	3.8
Improved goats yield	6.7	13.1	-13.8
Improved cattle yield	4.9	11.8	1.0
Improved agriculture and goats yields	7.0	14.7	-9.9
Improved agriculture and cattle yields	5.3	13.2	4.8
Improved livestock yields	11.5	25.4	-11.1
Improved agriculture and livestock yields	12.3	26.9	-7.2

Analysis of the policy options proposed by stakeholders

Table 2 summarizes the general management measures. Of the 102 observations, 64% correspond to changes in traditional activities (agriculture and livestock farming), 18.6% to the development of a new potential economic sector (i.e., tourism), and 17.6% to increased local services. Of the all observations, 27.5% refer to the management measures to increase production yields in agriculture and livestock activity, which converge with the potential leverage points (24 observations related to livestock yields, and four to agriculture yields). The local population and academia were the stakeholder groups that proposed a larger number of management measures (37% and 31%, respectively), which matches the identified leverage points. On the contrary, the regional BCS government concentrated 52% of the proposals in local services and subsidies, whereas only 0.09% of the proposed government measures were destined to increase production yields. Other management measures associated with traditional activities were related to: increase the added value of local products; improve local organization; reduce the negative effects of drought periods; diversify local economy and production.

Table 2. Number of policy options and management measures proposed by stakeholders. We grouped the observations by sectors and by groups of stakeholders. The management measures related to the identified leverage points are indicated by asterisks.

Sector	Type of policy options and management measures	Local actors	Government of BCS	Academia
Livestock activity	Investment in infrastructure and livestock equipment*	5	1	9
	Partial-stabled livestock herds*	1	0	2
	Subsidies: compensatory measures to recover livestock stocks	2	0	1
	Genetic improvement of livestock by hybridization*	2	0	1
	Fodder crops*	0	0	3
	Infrastructure for water collections and storage	0	1	2
	New marketing schemes for livestock products	2	2	5
	Diversification of livestock products	0	0	2
	Local cooperative for livestock activity	4	0	2
Agriculture	Investment in infrastructure and agricultural equipment*	2	1	1
	New marketing schemes for agricultural products	3	2	6
	Diversification of agricultural products	0	0	2
	Access to credits	0	0	1
Tourism	Tourism development (e.g. lodgment, restaurants, tourist routes, hiking trails)	2	2	9
	Sale of handicrafts	1	2	3
Services	Investment in public services	3	10	3
	Subsidies: program of temporary employment	0	2	0

DISCUSSION AND CONCLUSIONS

Our dynamic simulation model and the sensitivity analysis allowed us to identify the most sensitive places to intervene in a small-scale agro-system in Baja California Sur (Mexico). Improvement in livestock yields had the strongest impact. However, the best results were obtained by jointly improving agriculture and livestock yields. The depopulation process decelerated, and the population in the last decade of simulation slightly increased. Notwithstanding in all the management scenarios, the depopulation trend remained throughout the simulation period as a whole. Local actors and the academia were the stakeholders whose proposals agreed largely with the identified leverage points. As Meadows (1999) pointed out, stakeholders usually have an intuition about where the leverage points are located in a system. The regional BCS government focused on the proposals of public services and subsidies. This government was the most distant group to both the potential leverage points, and local actors' priorities. Closer cooperation between stakeholders is necessary to use public resources more efficiently, to take advantage of the further generated knowledge and to successfully implement management actions.

The leverage points examined herein are sensitive, but not miraculous places. Our results evidence that realistic improvements in livestock farming yields (Cepeda and Angulo 2013) and agriculture yields (Altieri 1999) would slightly improve local conditions, but not sufficiently to reverse the current decline process in a sustainable way. The identified leverage points are easy parameters to modify, but with limited effects on the overall system functioning (Meadows 1999, Abson *et al*. 2017). For example, our analysis highlighted that livestock activity was the best place to intervene, but we must consider that livestock farming is extremely vulnerable to extreme weather events, like droughts and hurricanes, which are historically frequent in this system and could be possibly exacerbated in the future due to climate change (Tenza *et al*., submitted). Focusing management measures on only increasing the relative weight of livestock activity is too risky. The examined management measures did not imply any change to the system´s structure (i.e., new stock variables, changes in the relationships between system components, feedbacks). Some structural changes (i.e., development of a new economic sector like tourism), which were also proposed by the stakeholders, may have a stronger repercussion on local dynamics. However, extensively exploring the effects of the management measures proposed by the stakeholders is necessary to determine this.

Our model has some limitations, which may overestimate the effects of the examined leverage points. These are the non inclusion of stochastic behaviors, which can affect the livestock dynamics, and not separating the population into age groups, which may restrain the recovery of this SES due to aging effects. It seems that small-scale SESs like this one, which is largely influenced by global drivers, are dragged by inertia. Local policy options may have a positive effect, but possibly more profound changes are needed to achieve sustainable dynamics. We cannot recognize the unsustainability of our global SES and pretend that small-scale SESs adapt harmoniously to it

(Challies *et al.* 2014). The socio-economic pressures on these SESs might be under our control, changes are needed on all scales.

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References

Abson DJ, Fischer J, Leventon J, *et al*. 2017. Leverage points for sustainability transformation. Ambio 46: 30–39.

Altieri MA. 1999. Applying agroecology to enhance the productivity of peasant farming systems in Latin America. Environ Dev Sustain 1: 197–217.

Balvanera P, Daw TM, Gardner TA, *et al*. 2017. Key features for more successful place-based sustainability research on social-ecological systems: a Programme on Ecosystem Change and Society (PECS) perspective. Ecol Soc 22, #14.

Barlas Y. 1996. Formal aspects of model validity and validation in system dynamics. Syst Dynam Rev 12: 183–210.

Cariño M, Breceda A, Ortega A, and Castorena L (Eds). 2013. Evocando el edén. Conocimiento, valoración y problemática del Oasis de Los Comondú. Barcelona, Spain: Icaria editorial.

Carpenter SR, Folke C, Norström A, *et al*. 2012. Program on ecosystem change and society: an international research strategy for integrated social-ecological systems. Curr Opin Environ Sustain 4: 134–138.

Cepeda R and Angulo CE. 2013. Reconversión productiva y comercialización de los productos pecuarios en las comunidades de San Miguel y San José de Comondú, B.C.S. In: Gámez AE (Ed.). Opciones de desarrollo en el oasis de Los Comondú, Baja California Sur, México. La Paz: Instituto Sudcaliforniano de Cultura.

Challies E, Newig J and Lenschow A. 2014. What role for social-ecological systems research in governing global teleconnections? Global Environ Chang 27: 32–40.

FAO. 2014. The State of Food and Agriculture: Innovation in family farming. Rome: FAO.

Gámez AE (Ed). Opciones de desarrollo en el oasis de Los Comondú, Baja California Sur, México. La Paz: Instituto Sudcaliforniano de Cultura.

González de Molina M and Toledo VM. 2014. The Social Metabolism. A Social-Ecological Theory of Historical Change. London: Springer.

Janssen MA, Anderies JM and Ostrom E. 2007. Robustness of Social-Ecological Systems to Spatial and Temporal Variability. Soc Nat Resour 20: 1–16.

Jørgensen SE and Fath BD. 2011. Fundamentals of Ecological Modelling: Applications in Environmental Management and Research. Amsterdam: Elsevier.

Meadows D. 1999. Leverage points: Places to intervene in a system. Hartland: The Sustainability Institute.

Millennium Ecosystem Assessment (MEA). 2005. Ecosystems and Human Well-being: Synthesis. Washington, DC: Island Press

Tenza A, Pérez I, Martínez-Fernández J, *et al*. 2017. Understanding the decline and resilience loss of a long-lived social-ecological system: insights from system dynamics. Ecol Soc 22: #15.

Tenza A, Martínez-Fernández J, Pérez I, *et al*. Resilience of small-scale social-ecological systems: trade-off and synergies of global and regional changes. Submitted to Global Environ Chang.

Turner BL, Tidwell V, Fernald A, *et al*. 2016. Modeling Acequia Irrigation Systems Using System Dynamics: Model Development, Evaluation, and Sensitivity Analyses to Investigate the Effects of Socio-Economic and Biophysical Feedbacks. Sustain 8: #1019.

Vennix JAM. 1996. Group Model Building. Facilitating team learning using system dynamics. Chichester, United Kingdom: John Wiley & Sons.

Young OR, Berkhout F, Gallopin G, *et al*. 2006. The globalization of socio-ecological systems: An agenda for scientific research. Global Environ Chang 16: 304–316.

CONCLUSIONES

*La cañada del oasis de Los Comondú (fotografía de Andrés Giménez Casalduero)

1. Los modelos cualitativos construidos a partir del proceso de conceptualización del enfoque de la Dinámica de Sistemas permiten establecer las hipótesis estructurales que explican el comportamiento histórico observado de sistemas socioecológicos, profundizando en las relaciones causa-efecto, a diferencia de otros enfoques recurrentes en la literatura que permanecen todavía con un alto nivel de abstracción.

2. El proceso de conceptualización de un sistema, es un proceso iterativo, reflexivo y de aprendizaje sobre el sistema de estudio. A pesar de mantenerse a nivel cualitativo, es la etapa más larga e importante del proceso del proceso de modelado, ya que las demás etapas dependen de ésta.

3. El uso de técnicas de investigación social en el proceso de conceptualización del sistema, especialmente la observación participante, contribuye sustancialmente a la construcción de una fuerte relación de confianza mutua con los actores locales. Condición indispensable para el éxito de procesos participativos orientados a la toma de decisiones.

4. El modelo "SESSMO" simula el comportamiento histórico de las principales variables del sistema socioecológico del oasis de Los Comondú con un buen ajuste entre datos simulados y observados. Las pruebas de validación demostraron su robustez estructural y su validez para los objetivos propuestos.

5. Las políticas de desarrollo regional implementadas en Baja California Sur en la segunda mitad del siglo XX influenciaron la dinámica del sistema socioecológico del oasis de Los Comondú de la siguiente manera: i) la expansión agrícola de carácter agroindustrial y la concentración de la inversión pública en las zonas turísticas costeras fomentaron el éxodo rural, ii) el reparto de tierras comunales a través de la creación del "ejido Comondú" frenó el proceso de despoblamiento, mejoró los indicadores de empleo y servicios, y promovió el establecimiento de la ganadería como la principal actividad productiva y económica del oasis. Esto último, sin embargo, ha incrementado la sensibilidad del sistema a la variación de la precipitación, y los eventos climáticos extremos de sequías y huracanes.

6. Los factores asociados a procesos globales (i.e. clima y mercados) tienen un mayor peso en la dinámica del sistema que las políticas de desarrollo regional. No obstante, y al contrario de lo que esperábamos, ni los efectos de los procesos asociados a procesos globales, ni las políticas regionales explican por

si solas el origen del declive de este sistema socioecológico. Factores endógenos contemplados en el modelo, como el empleo y la economía local, y posibles factores no contemplados todavía, como la distribución de la tierra, pueden tener un mayor peso en el origen del declive.

7. El efecto sinérgico de las variables externas climáticas y económicas sobre la dinámica del sistema evidencia su vulnerabilidad ante la doble exposición al cambio climático y a la globalización económica.

8. La natalidad del ganado caprino y bovino, la producción de queso por cabra, el peso del ganado bovino a la venta, y el rendimiento agrícola son los parámetros más sensibles del sistema intervenibles por medidas de gestión, como pudiera ser la asistencia técnica o implementación de paquetes tecnológicos.

9. La mejora del rendimiento ganadero (bovino y caprino) es la medida de gestión que más influye en la dinámica del sistema. Sin embargo, las mejoras cifras, en relación con el objetivo de frenar o incluso revertir el despoblamiento del oasis, se obtienen al mejorar conjuntamente el rendimiento agrícola y el ganadero. Se ralentiza el proceso de despoblamiento y durante la última década de la simulación hay un incipiente crecimiento poblacional. No obstante, la dinámica hacia el declive del sistema socioecológico es mantenida durante casi todo el periodo de simulación bajo todos los escenarios de gestión.

10. Los resultados de la simulación de escenarios demuestran la inercia de este sistema socioecológico. Se requieren de cambios estructurales para contrarrestar de manera sostenible esta tendencia.

11. La población del oasis y la academia son los actores que mediante sus propuestas se aproximan más a los potenciales puntos de palanca del sistema. El gobierno regional de Baja California Sur es el actor con las propuestas más distantes a estos puntos de palanca del sistema, pero también el más distante a las demandas de la población del oasis.

12. La presente tesis constituye una de las primeras investigaciones a largo plazo sobre un sistema socioecológico tradicional que cuantitativamente analiza el proceso de declive de este tipo de sistemas a través de un modelo de simulación cuantitativo, determina el peso relativo de los efectos de los cambios ambientales y socioeconómicos en las escalas regional y global sobre este declive, e identifica y mide las interacciones entre las escalas local, regional y global.

13. El conocimiento ecológico local además de ser una rica fuente de información para conceptualizar el sistema bajo estudio, también constituye una fuente de datos cuantitativos y semi-cuantitativos útiles para la parametrización y validación de los modelos de simulación dinámica.

14. El estudio de los sistemas socioecológicos no debe detenerse en la descripción cualitativa del sistema, especialmente cuando han de derivarse recomendaciones de medidas de gestión, dado que la complejidad de estos sistemas desafía la capacidad de nuestros modelos mentales, por lo que no es fácil identificar correctamente las consecuencias que se derivan de hipótesis cualitativas. Se debe avanzar en las aproximaciones más formales para el estudio y análisis de estos sistemas, a través de herramientas como la simulación dinámica, utilizada en esta tesis, y complementadas con aproximaciones protagonizadas por las comunidades locales.

Conclusions

1. The qualitative models developed from the conceptualization process of the System Dynamics approach allow the establishment of the structural hypotheses to explain the historical behavior of social-ecological systems, deepening into the cause-effect relationships, unlike other recurrent approaches in the literature that still remain at a high level of abstraction.

2. The conceptualization process is an iterative, reflective and learning process about the study system. Although this step remains at qualitative level, it is the longest and most important step in the modeling process, since the other stages depend on it.

3. The use of social research techniques in the conceptualization process, especially the participant observation, contributes substantially to the construction of a strong relationship of mutual trust with local actors. This is an essential condition for the success of participatory processes oriented to decision making.

4. The "SESSMO" model simulated the historical behavior of the main variables of the system with a good agreement between simulated and observed data. The validation tests demonstrated its structural robustness and its validity for the proposed objectives.

5. Regional development policies implemented in Baja California Sur in the second half of the 20th century influenced the dynamics of the socio-ecological system of the oasis of Comondú oasis as follows: i) the agro-industrial development and the concentration of public investment on the coastal tourist areas promoted the rural exodus; ii) the delivery of common lands to landless people, through the creation of the "ejido Comondú", halted the depopulation process, improved the employment and services indicators, and promoted the establishment of livestock farming as the main productive and economic activity of the oasis. The latter, however, has increased the sensitivity of the system to changes in rainfall and to extreme climatic events, such as droughts and hurricanes.

6. Factors associated with global processes (i.e., climate and markets) play a greater role in the dynamics of the system than regional development policies. However, contrary to what we expected, neither the effects of processes associated with global processes nor regional policies, can explain by themselves the origin of the decline of this social-ecological system. Endogenous factors considered in the model, such as employment and local

economy, and possible factors not yet included, such as land distribution, may have a greater role in the origin of the decline.

7. The synergistic effect of the climatic and economic external variables on the overall dynamics shows the vulnerability of this social-ecological system to the double exposure to climate change and economic globalization.

8. The birth rate of cattle, the birth rate of goats, the cheese production per goat, the weight of cattle for sale, and the yield of irrigated land are the most sensitive parameters of the system that can be intervened through management measures, such as technical assistance or implementation of technological packages.

9. The improvement of livestock yields (cattle and goats) is the management measure that influences heavily the system's dynamics. However, the best results were obtained by jointly improving agriculture and livestock yields. The depopulation process decelerated, and the population in the last decade of simulation slightly increased. Notwithstanding in all the management scenarios, the depopulation trend remained throughout the simulation period as a whole.

10. The simulation results of scenarios demonstrate the inertia of this social-ecological system. Structural changes are needed to offset this trend in a sustainable manner.

11. Local actors and the academia are the stakeholders whose proposals agree largely with the identified leverage points. The regional BCS government focused on the proposals of public services and subsidies. This government is the most distant group to both the potential leverage points, and local actors' priorities.

12. The present thesis is one of the first long-term studies on a traditional social-ecological system that quantitatively analyzes the decline process of this type of systems by means of a quantitative simulation model, determines the relative weight of the effects of environmental changes at regional and global scales on this decline and identifies and measures the interactions between local, regional and global scales.

13. The local ecological knowledge, besides being a rich source of information to conceptualize the system under study, is also a source of quantitative and semi-quantitative data useful for the parameterization and validation of dynamic simulation models.

14. This research confirms the importance of conducting quantitative models to understand the dynamics of complex systems, especially if the goal is to propose management measures or policy recommendations. In complex systems, the existence of feedbacks, delays, trade-offs and synergies challenge our understanding of the system's behavior, and can lead to misleading conclusions. It is necessary to advance in formal approaches for the study and analysis of these systems by means of dynamic simulations, as showed in this thesis, complemented with approaches carried out by local communities.

BIBLIOGRAFÍA

*Huerta de Don Francisco Javier Murillo Ceseña (fotografía de Andrés Giménez Casalduero)

Acosta-Naranjo R. 2002. Los entramados de la diversidad. Antropología Social de la Dehesa. Colección raíces nº16, Diputación de Badajoz, Badajoz, España.

Allen CR, Angeler DG, Garmestani AS, Gunderson LH, Holling CS. 2014. Panarchy: Theory and Application. *Ecosystems* 17, 578–589.

Altieri, M. A. 1999. Applying agroecology to enhance the productivity of peasant farming systems in Latin America. *Environment, Development and Sustainability* 1:197–217.

Anadón JD, Giménez A, Ballestar R, Pérez I. 2009. Evaluation of local ecological knowledge as a method for collecting extensive data on animal abundance. *Conservation Biology* 23, 617–625.

Anderies JM, Janssen MA, and Ostrom E. 2004. A framework to analyze the robustness of socialecological systems from an institutional perspective. *Ecology and Society* 9(1): #18.

Arriaga, L., and R. Rodríguez-Estrella. 1997. Los Oasis de la Península de Baja California. La Paz, Mexico: CIBNOR.

Bai ZG, Dent DL, Olsson L, Schaepman ME. 2008. Global Assessment of Land Degradation and Improvement. Identification by Remote Sensing. Report 2008/01. ISRIC-World Soil Information. Wageningen, Holanda.

Balvanera, P., Daw, T.M., Gardner, T.A., Martín-López, B., Norström, A.V., Speranza, C.I., Spierenburg, M., Bennet, E.M., Farfan, M., Hamann, M., Kittinger, J.N., Luthe, T., Maas, M., Peterson, G.D., Perez-Vedin, G. 2017. Key features for more successful place-based sustainability research on social-ecological systems: a Programme on Ecosystem Change and Society (PECS) perspective. *Ecology and Society* 22, #14.

Banos-González, I., J. Martínez-Fernández, and M. A. Esteve. 2015. Dynamic integration of sustainability indicators in insular socio-ecological systems. *Ecological Modelling* 306: 130–144.

Banos-González, I., J. Martínez-Fernández, and M. A. Esteve. 2016. Using dynamic sustainability indicators to assess environmental policy measures in Biosphere Reserves. *Ecological indicators* 67: 565–576.

Baur, I., and C. R. Binder. 2015. Modeling and assessing scenarios of common property pastures management in Switzerland. *Ecological Economics* 119: 292–305.

Becker CD, Ghimire K. 2003. Synergy between traditional ecological knowledge and conservation science supports forest preservation in Ecuador. *Conservation Ecology* 8: #1.

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

Berkes F, Colding J, and Folke C. 2003. Navigating social-ecological systems. Building Resilience for Complexity and Change. Cambridge University Press, Cambridge.

Brander, J. A., and M. S. Taylor. 1998. The Simple Economics of Easter Island: A Ricardo-Malthus Model of Renewable Resource Use. *The American Economic Review* 88 (1): 119–138.

Cariño M, Breceda A, Ortega A, and Castorena L (Eds). 2013. Evocando el edén. Conocimiento, valoración y problemática del Oasis de Los Comondú. Barcelona, Spain: Icaria editorial.

Cariño M, Breceda A, y Tenza A. 2016. Los oasis: sistemas socioambientales tradicionales de la península de Baja California. En: Moreno-Calles, A.I., Casas, A., Toledo, V.M., y Vallejo-Ramos, M. (Eds.). Etnoagroforestería en México. Universidad Autónoma Nacional de México, Escuela Nacional de Estudios Superiores Unidad de Morelia, Instituto de Investigaciones en Ecosistemas y Sustentabilidad, Ciudad de México, pp. 149–169.

Cariño, M. 2001. La oasisidad, núcleo de la cultura sudcaliforniana. *Gaceta Ecológica* 60: 57–69.

Carlson JM, and Doyle J. 2002. Complexity and robustness. *PNAS* 99, 2538–2545.

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., Spierenburg, M. 2012. Program on ecosystem change and society: an international research strategy for integrated social-ecological systems. *Current Opinion in Environmental Sustainability* 4, 134–138.

Ceballos G, Ehrlich PR, Barnosky AD, García A, Pringle RM, Palmer TM. 2015. Accelerated modern human–induced species losses: Entering the sixth mass extinction. *Science Advances* 1(5): 1–5.

Collantes, F. 2007. The Decline of Agrarian Societies in the European Countryside: A case study of Spain in the Twentieth Century. *Agricultural History* 81: 76–97.

Crutzen PJ and Stoermer EF. 2000. The "Anthropocene". *Global Change NewsLetter* 41, 17–18.

Dale, V. H., R. V. O'Neill, M. Pedlowski, and F. Southworth. 1993. Causes and effects of land-use change in central Rondonia, Brazil. *Photogrammetric Engineering & Remote Sensing* 59: 997–1005.

de Grenade, R. , and G. P. Nabhan. 2013. Baja California peninsula oases: An agro-biodiversity of isolation and integration. *Applied Geography* 41: 24–35.

Egea-Fernández JM y Egea-Sánchez JM. 2010. Guía del Paisaje Cultural Tierra de Iberos. Una perspectiva agroecológica. SEAE.

FAO. 2014. The State of Food and Agriculture: Innovation in family farming. Rome: FAO.

Forrester, J. W. 1958. Industrial Dynamics: A Major Breakthrough for Decision Makers. *Harvard Business Review* 36: 37–66.

Forrester, J. W. 1961. Industrial dynamics. Waltham, Massachusetts: Pegasus communications.

Forrester, J. W. 1992. Policies, decisions and information sources for modeling. *European Journal of Operational Research* 59: 42–63.

Gadgil M, Berkes F, and Folke C. 1993. Indigenous knowledge for biodiversity conservation. *Ambio* 22, 151–156.

González de Molina M and Toledo VM. 2014. The Social Metabolism. A Social-Ecological Theory of Historical Change. London: Springer.

Haag D. Kaupenjohann M. 2001. Parameters, prediction, post-normal science and the precautionary principle – a roadmap for modelling for decision-making. *Ecological Modelling* 144: 45-60.

Hanspach J, Hartel T, Milcu AI, Mikulcak F, Dorresteijn I, Loos J, von Wehrden H, Kuemmerle T, Abson D, Kovács-Hostyánszki A, Báldi A, Fischer J. 2014. A holistic approach to studying social-ecological systems and its application to southern Transylvania. *Ecology and Society* 19, #32.

Huntington HP. 2000. Using traditional ecological knowledge in science: methods and applications. *Ecological Applications* 10, 1270–1274.

Janssen, M. A., J. M. Anderies, and E. Ostrom. 2007. Robustness of Social-Ecological Systems to Spatial and Temporal Variability. *Society and Natural Resources* 20: 1–16.

Kelly RA, Jakeman AJ, Barreteau O, Borsuk ME, ElSawah S, Hamilton SH, Henriksen HJ, Kuikka S, Maier HR, Rizzoli AE, van Delden H, and Voinov AA. 2013. Selecting among five common modelling approaches for integrated environmental assessment and management. *Environmental Modelling & Software*, 47: 159–81.

Luna-Reyes, L. F., and D. L. Andersen. 2003. Collecting and analyzing qualitative data for system dynamics: methods and models. *System Dynamics Review* 19: 271–296.

Martínez-Fernández J, Esteve-Selma MÁ. (2004). Dynamics of water scarcity on irrigated landscapes: Mazarron and Aguilas in south-eastern Spain. *System Dynamics Review*, 20: 117–37.

Martínez-Fernández, J., M. A. Esteve-Selma, I. Baños-González, F. Carreño, and A. Moreno. 2013. Sustainability of Mediterranean irrigated agro-landscapes. *Ecological Modelling* 248: 11–19.

Meadows, D. H., D. L. Meadows, J. Randers, and W. W. Behrens III. 1972. The limits to growth. New York: Universe Books.

Millennium Ecosystem Assessment (MEA). 2005. Ecosystems and Human Well-being: Synthesis. Washington, DC: Island Press.

Motesharrei, S., J. Rivas, and E. Kalnay. 2014. Human and nature dynamics (HANDY): Modeling inequality and use of resources in the collapse or sustainability of societies. *Ecological Economics* 101: 90–102.

O´Brien KL, Leichenko RM. 2000. Double exposure: assessing the impacts of climate change within the context of economic globalization. *Global Environmental Change* 10, 221–232.

Palomo I, Martín-LópezB, López-Santiago C, and Montes C. 2011. Participatory scenario planning for protected areas management under the ecosystem services framework: the doñana social ecological system in southwestern Spain. *Ecology and Society* 16(1): #23.

Parry L, Peres CA. 2015. Evaluating the use of local ecological knowledge to monitor hunted tropical-forest wildlife over large spatial scales. *Ecology and Society* 20, #15.

Pérez, I., A. Tenza, J. D. Anadón, J. Martínez-Fernández, A. Pedreño, and A. Giménez. 2012. Exurban sprawl increases the extinction probability of a threatened tortoise due to pet collections. *Ecological Modelling* 245: 19–30.

Pérez-García JM, Botella-Robles F, Galina T, Arnaud G, Pérez I, y Giménez A. 2013. Estructura y funcionamiento dinámico del oasis. En: Cariño M, Breceda A, Ortega A, y Castorena L (Eds). Evocando el edén. Conocimiento, valoración y problemática del Oasis de Los Comondú. Barcelona, España: Icaria editorial, pp 139–151.

Perfecto, I., J. Vandermeer, and A. Wright. 2009. Nature's Matrix: Linking Agriculture, Conservation and Food Sovereignty. London, United Kingdom: Earthscan.

Randers J. 1980. Guidelines for model conceptualization. Pages 117–139 in J. Randers, editor. Elements of the System Dynamics Method. Cambridge, Massachusetts: MIT Press.

Reed MS. 2008. Stakeholder participation for environmental management: A literature review. *Biological Conservation* 141, 2417–2431.

Richardson G. P., and A. L. Pugh III. 1981. Introduction to System Dynamics Modeling with DYNAMO. Cambridge, Massachusetts: Productivity Press.

Roberts, N., D. F. Andersen, R. M. Deal, M. S. Garet, and W. A. Shaffer. 1983. Introduction to computer simulation: the systems dynamics approach. United States of America: Addison-Wesley.

Rockström J, Steffen W, Noone K, Persson Å, Chapin FS III, Lambin E, Lenton TM, Scheffer M, Folke C, Schellnhuber H, Nykvist B, De Wit CA, Hughes T, van der Leeuw S, Rodhe H, Sörlin S, Snyder PK, Costanza R, Svedin U, Falkenmark M, Karlberg L, Corell RW, Fabry VJ, Hansen J, Walker B, Liverman D, Richardson K, Crutzen P, and Foley J. 2009. Planetary boundaries:exploring the safe operating space for humanity. *Ecology and Society* 14(2): #32.

Sanga GJ, and Mungatana ED. 2016. Integrating ecology and economics in understanding responses in securing land-use externalities internalization in water catchments. *Ecological Economics* 121: 28–39.

Sterman JD. 2000. Business Dynamics: Systems Thinking and Modeling for a Complex World. Boston: Irwin/McGraw-Hill.

Tengö M, and Belfrage K. 2004. Local management practices for dealing with change and uncertainty: a cross-scale comparison of cases in Sweden and Tanzania. *Ecology and Society* 9: #4.

Toledo VM, Barrera-Bassols N. 2008. La memoria biocultural. La importancia ecológica de las sabidurías tradicionales. Barcelona, España: Icaria Editorial.

Toledo VM. 2012. Diez tesis sobre la crisis de la modernidad. *Polis Revista Latinoamericana* 33, 1–7.

Turner G. 2014. 'Is Global Collapse Imminent?', MSSI Research Paper No. 4, Melbourne Sustainable Society Institute, The University of Melbourne.

Vennix JAM. 1996. Group Model Building. Facilitating team learning using system dynamics. Chichester, United Kingdom: John Wiley & Sons.

Vidal-Legaz B, Martínez-Fernández J, Sánchez-Picón A, and Pugnaire F. 2013. Trade-offs between maintenance of ecosystem services and socio-economic development in rural mountainous communities in southern Spain: a dynamic simulation approach. *Journal of Environmental Management* 131: 280–297.

Wolstenholme E. 1990. System Enquiry: A System Dynamics Approach. New York: John Wiley & Sons.

Xiao-Qing Z, Hui R, Qi Y, Chun-lan H, and Hong-hui Y. 2012. Scenarios Simulation on Carrying Capacity of Water Resources in Kunming City. *Procedia Earth and Planetary Science* 5: 107–112.

Young OR, Berkhout F, Gallopin G, *et al*. 2006. The globalization of socio-ecological systems: An agenda for scientific research. *Global Environmental Change* 16: 304–316.

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