UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO
POSGRADO EN CIENCIAS DE LA SOSTENIBILIDAD
ENTIDAD

ANÁLISIS SOCIO-ECOLÓGICO DEL SISTEMA DE APROVECHAMIENTO DEL BORREGO CIMARRÓN (*Ovis canadensis*) EN BAJA CALIFORNIA SUR

TESIS
QUE PARA OPTAR POR EL GRADO DE
DOCTORA EN CIENCIAS DE LA SOSTENIBILIDAD

PRESENTA:
HILDA CONSUELO ZAMORA MALDONADO

DRA, V. SOPHIE AVILA FOUCAT, (TUTORA PRINCIPAL)
INSTITUTO DE INVESTIGACIONES ECONÓMICAS, UNAM

DR. ALEJANDRO VELÁZQUEZ MONTES, (MIEMBRO DE COMITÉ TUTOR)
CENTRO DE INVESTIGACIONES EN GEOGRAFÍA AMBIENTAL, UNAM

DR. ENRIQUE MARTÍNEZ MEYER, (MIEMBRO DE COMITÉ TUTOR)
INSTITUTO DE BIOLOGÍA, UNAM

DR. VÍCTOR SÁNCHEZ-CORDERO DÁVILA, (REVISOR)
INSTITITO DE BIOLOGÍA, UNAM

DR. DANIEL ALFREDO REVOLLO FERNÁNDEZ, (REVISOR)
DEPARTAMENTO DE ECONOMÍA, UAM AZCAPOTZALCO

DR. ALEJANDRO VELÁZQUEZ MONTES, (REVISOR)
CENTRO DE INVESTIGACIONES EN GEOGRAFÍA AMBIENTAL, UNAM

DR. ENRIQUE MARTÍNEZ MEYER, (REVISOR)
INSTITUTO DE BIOLOGÍA, UNAM

CIUDAD UNIVERSITARIA, CIUDAD DE MÉXICO, OCTUBRE 2022

UNAM POSGRADO
Ciencias de la Sostenibilidad

Coordinación de Estudios de Posgrado
Ciencias de la Sostenibilidad
Oficio: CGEP/PCS/122/22
Asunto: Asignación de Jurado

M. en C. Ivonne Ramírez Wence
Directora General de Administración Escolar
Universidad Nacional Autónoma de México
Presente

Me permito informar a usted, que el Comité Académico del Programa de Posgrado en Ciencias de la Sostenibilidad, en su sesión 50 del 10 de septiembre del 2019, aprobó el jurado para la presentación del examen para obtener el grado de **DOCTORA EN CIENCIAS DE LA SOSTENIBILIDAD**, de la alumna **Zamora Maldonado Hilda Consuelo** con número de cuenta **95002428** con la tesis titulada "Análisis socio-ecológico del sistema de aprovechamiento de borrego cimarrón (Ovis canadensis) en Baja California Sur", bajo la dirección de la Dra. Véronique Sophie Avila Foucat.

PRESIDENTA:	DR. VÍCTOR MANUEL GUILLERMO SÁNCHEZ CORDERO DÁVILA
VOCAL:	DR. DANIEL ALFREDO REVOLLO FERNÁNDEZ
SECRETARIO:	DR. ENRIQUE MARTÍNEZ MEYER
VOCAL:	DR. ALONSO AGUILAR IBARRA
VOCAL:	DR. JOSÉ ALEJANDRO VELÁZQUEZ MONTES

Sin más por el momento me permito enviarle un cordial saludo.

ATENTAMENTE,

"POR MI RAZA HABLARA EL ESPIRITU"
Cd. Universitaria, Cd. Mx., 30 de septiembre de 2022.

Dr. Alonso Aguilar Ibarra
Coordinador
Posgrado en Ciencias de la Sostenibilidad, UNAM

AGRADECIMIENTOS

A la Universidad Nacional Autónoma de México por haberme brindado un espacio de enriquecimiento académico y cultural tan amplio.

Al Posgrado en Ciencias de la Sostenibilidad de la Universidad Nacional Autónoma de México

Al Consejo Nacional de Ciencia y Tecnología (CONACYT), por la beca otorgada para llevar a cabo los estudios de doctorado

Al Proyecto PAPIIT-UNAM-IN301516

A mi asesora principal Dra. Sophie Avila Foucat por su trascendental apoyo y experiencia académica a lo largo de mi formación en el doctorado y por considerarme en múltiples proyectos de investigación.

A mi comité tutoral, Dr. Alejandro Velázquez Montes y Dr. Enrique Martínez Meyer, por su valioso aporte académico.

A mi comité revisor, Dr. Alonso Aguilar Ibarra, Dr. Daniel Revollo Fernández y al Dr. Víctor Sánchez Cordero, por su valiosa retroalimentación.

A la CONANP, en particular al Área de Protección de Flora y Fauna Valle de los Cirios y a Víctor Sánchez Sotomayor por el apoyo en la logística de movilidad proporcionada para el desarrollo de este proyecto.

Al Ejido Alfredo Vladimir Bonfil por haberme abierto las puertas de sus hogares y permitirme conocer más sobre el borrego cimarrón.

AGRADECIMIENTOS A TÍTULO PERSONAL

A Edmundo, por ser la ceiba que nos cobija y protege bajo su copa, por ser el compañero de vida soñado, por compartir el gusto por el mundo académico, por los consejos y guía, por ser un extraordinario ser humano y padre de Emiliano.

A mi hijo Emiliano por los grandes momentos de risas imparables que alimentan mi alma, por acompañarme día y noche en el vientre en los momentos de trabajo más exhaustivos durante el desarrollo del artículo central de esta tesis, te amo.

A Juanita, mi mamá por su ejemplo de constancia, dedicación y extraordinaria inteligencia que me seguirá inspirando.

A Fernando, mi papá por su apoyo siempre incondicional, por el espíritu de amor y libertad con el que me educó ¡gracias hasta donde quiera que estés!

A mis hermanos Heriberto y Roberto por su amistad incondicional.

A Alejandra Ramírez por la agradable compañía de colaboración académica y amistad incondicional.

A Jimena Deschamps por el apoyo brindado durante la última fase de la investigación en campo. Principalmente por el valor de acompañar a una embarazada de 5 meses a levantar encuestas en el Ejido Bonfil, cruzar el mar de Cortés en avioneta, presenciar el avistamiento de más de 200 ballenas en la laguna ojo de liebre, hospedarse en medio del desierto, convivir con la fauna local, cantar “Me and Bobby McGee” con los hippies de la tercera edad que bajan de USA a la península y finalmente regresar sin un rasguño a CDMX ¡gracias!

A la memoria de Fernando Zamora (1949-2021),
mi papá

ÍNDICE GENERAL

RESUMEN

El esfuerzo de manejo y conservación de especies de vida silvestre en México requiere la consideración conjunta de las dimensiones humana y ecológica. Particularmente, el manejo del borrego cimarrón (*Ovis canadensis*) en el país se basa en un instrumento de política ambiental denominada "Unidad de Manejo para la Conservación de la Vida Silvestre (UMA)" que permite un aprovechamiento sostenible en territorios específicos. En este estudio se considera el término de territorio como un espacio geográfico con una identidad especial (Medeiros, 2016) en donde se expresa el resultado de las interacciones históricas entre las fuerzas socioeconómicas que gobiernan el acceso a los recursos naturales (Burgos & Velázquez, 2019). En el estado de Baja California Sur (BCS) la política de conservación del borrego cimarrón opera desde 1998 en ejidos. Bajo el esquema UMA, los ejidatarios pueden recaudar ingresos de las actividades de caza deportiva y reinvertirlos en la conservación del hábitat y el desarrollo de infraestructura. Esta investigación desarrolló dos modelos numéricos: a) un modelo dinámico exploratorio que se utilizó para identificar los umbrales por debajo de los cuales el borrego cimarrón puede ser explotado de manera sostenible bajo la política UMA existente y analizar su resiliencia a largo plazo. El modelo b) un modelo de aptitud del hábitat[1] que integra una información de distribución potencial georreferenciada a este análisis. Se emplearon estas dos herramientas de modelado numérico para evaluar el efecto potencial del cambio climático regional (cambios de precipitación y temperatura) en la aptitud del hábitat de las poblaciones del borrego cimarrón, lo cual permite respaldar estrategias de gestión resilientes al dirigir la atención hacia polígonos que pueden ser adecuados para la implementación de las estrategias de gestión en condiciones bioclimáticas futuras. El presente análisis explora la interacción de la incertidumbre del cambio climático en el contexto de este sistema socio-ecológico. Los datos de presencia de la especie se obtuvieron de los censos aéreos de población en BCS (Lee, 2016). Los datos económicos se obtuvieron de entrevistas y encuestas a los actores sociales en el ejido Alfredo V. Bonfil, BCS. Los resultados indican que las variaciones de temperatura y precipitación con respecto al registro histórico pueden ejercer una presión importante tanto para la especie como en las actividades económicas que dependen de ella. El presente análisis sugiere que la actualización del instrumento de política debe integrar estrategias adaptativas de gestión dadas las inminentes condiciones climáticas hacia futuro. Estas estrategias, podrían aumentar la resiliencia de este sistema socio-ecológico. Finalmente se considera que este análisis se puede ampliar considerando múltiples especies, explorando estrategias que empleen una variedad amplia de opciones de políticas ambientales, es posible también aprovechar el potencial de aprendizaje a través de la exploración con diferentes parámetros en los modelos, los cual facilita el análisis riguroso de los objetivos con los que las partes interesadas en de gestión de la vida silvestre pueden necesitar comprometerse ante el cambio climático.

[1] Aptitud del hábitat: traducción del concepto en inglés "habitat suitability"

ABSTRACT

The management and conservation effort of wildlife species in Mexico requires the joint consideration of the human and ecological dimensions. The bighorn sheep (*Ovis canadensis*) management in the country is based on an environmental policy called "Management Unit for the Wildlife Conservation (UMA)" which allows sustainable management in specific territories. In the state of Baja California Sur (BCS) the bighorn sheep policy conservation has been operating since 1998 in ejidos (i.e., land tenure). Under the UMA scheme, people in the ejido can collect revenues from sport hunting activities and reinvest these on habitat conservation and infrastructure development. This research developed two numerical models: a) an exploratory dynamic model which was used to identify the thresholds under which the bighorn sheep can be managed sustainably under the existing UMA policy and assesses its long-term resilience and model b) a habitat suitability model that integrates a geo-referencing potential distribution information to this analysis. These two numerical modeling tools were used to assess the potential effect of regional climate change (changes in precipitation and temperature) on the habitat suitability of bighorn sheep populations, thereby supporting resilient management strategies by targeting polygons. that may be suitable for the implementation of management strategies in future bioclimatic conditions. The analysis explores the interaction of climate change uncertainty in the context of this socio-ecological system. The data on the presence of the species were obtained from aerial population censuses in BCS (Lee, 2016). The economic data was obtained from interviews and surveys of social actors in the ejido Alfredo V. Bonfil, BCS. The results indicate that variations in temperature and precipitation with respect to the historical record can exert significant pressure both on the species and on the economic activities that depend on it. This analysis suggests that updating the policy instrument should integrate adaptive management strategies given the imminent climatic conditions in the future. These strategies could increase the resilience of this socio-ecological system. Finally, it is considered that this analysis can be extended considering multiple species, exploring strategies that employ a wide variety of environmental policy options, it is also possible to take advantage of the learning potential through the exploration with different parameters in the models, which facilitate the Rigorous analysis of the goals that wildlife management stakeholders may need to commit to in the face of climate change.

I. INTRODUCCIÓN

1.1. La gestión de sistemas de aprovechamiento de recursos naturales en el contexto de la sostenibilidad

La solución de los desafíos contemporáneos de sostenibilidad requiere la consideración de sistemas acoplados, de marcos de análisis a largo plazo, de objetivos múltiples y de una profunda incertidumbre (Hull et al., 2015; Liu et al., 2013). Por ejemplo, la gestión sostenible de los ecosistemas, la planificación en torno a los recursos naturales y la adaptación y mitigación del cambio climático requieren la consideración conjunta de los sistemas naturales y humanos. Estos sistemas están altamente conectados, ya que los cambios en el comportamiento humano y la configuración del entorno natural o ecológico a menudo inducen cambios en las instituciones e incentivos humanos (Guerry et al., 2015). Por el contrario, el cambio de las preferencias humanas, la tecnología y las instituciones define significativamente las trayectorias de desarrollo de los sistemas de gestión y aprovechamiento de recursos naturales (Ostrom, 2005). A menudo, si estas interacciones no se monitorean y regulan, uno o ambos sistemas dejan de funcionar de manera sostenible (Hull et al., 2015; Ostrom, 2009). Por ejemplo, en el contexto del cambio climático global acelerado, las emisiones antropogénicas aumentan la concentración creciente de gases de efecto invernadero (GEI) en la atmósfera, lo cual desencadena desequilibrios climáticos (por ejemplo, cambios en los patrones de precipitación, temperaturas más altas) que pueden inducir daños irreversibles en los ecosistemas -por ejemplo, pérdida de biodiversidad- (Bálint et al., 2011; Pires et al., 2018) y en la economía -por ejemplo, mayor desigualdad- (Köberle et al., 2021).

En los últimos años, el cambio climático ha constituido un gran desafío para la formulación de políticas públicas, debido a la necesidad de una acción urgente (Parker et al., 2020) que tenga como objetivo abordar tanto sus causas como su impacto en los distintos niveles, desde el global al local (D’Almeida Martins & da Costa Ferreira, 2011).

La Tierra se ha calentado 1.09 C desde la época preindustrial y muchos cambios, como el aumento del nivel del mar y el derretimiento de los glaciares, son ahora prácticamente irreversibles. Dado que ya no es posible escapar del cambio climático causado por los humanos, las acciones de política con énfasis en abordar el impacto y, por lo tanto, las estrategias de adaptación son necesarias para impulsar la resiliencia de sistemas socio-ecológicos (SSEs) vulnerables (IPCC, 2021b).

Uno de los enfoques que se ha planteado para atender soluciones de largo plazo es el manejo adaptativo (Murray & Marmorek, 2003; Owen, 2020; Perry et al., 2020), el cual hace énfasis en el impacto del cambio climático como una fuente importante de incertidumbre para la gestión de los sistemas de aprovechamiento y conservación a escala global. Además, se enfoca en la gestión de la resiliencia como elemento central en el proceso de gestión adaptativa. Recientemente, la adaptación basada en ecosistemas (AbE) la cual involucra a personas que utilizan la biodiversidad y los servicios de los ecosistemas para adaptarse a los efectos adversos del cambio climático y promover el desarrollo sostenible. Es también una estrategia para adaptarse al cambio climático que aprovecha las soluciones y los servicios de los ecosistemas basados en la naturaleza. Por ejemplo, la protección de hábitats costeros como los manglares proporciona defensas naturales contra inundaciones; la reforestación puede frenar la desertificación y recargar el suministro de agua subterránea en tiempos de sequía; y los cuerpos de agua como ríos y lagos proporcionan drenaje natural para reducir las inundaciones; la reintroducción y translocación de fauna silvestre supone una estrategia para la conservación de la biodiversidad (Helena, 2020; Langridge et al., 2020a, 2021; Ramos et al., 2018).

Sin embargo, la implementación y análisis de políticas en el contexto de la sostenibilidad es un desafío. Primero, las esferas (o subsistemas) humana y natural son sistemas complejos: las dependencias de la trayectoria en ambas requieren la consideración de amplios marcos de tiempo, y sus interacciones no lineales inducen un comportamiento dinámico que es difícil de anticipar y caracterizar. En segundo lugar, la profunda incertidumbre afecta a ambas esferas, ya que los expertos y los actores locales a menudo discrepan sobre la representación causal de estos sistemas, el valor de los parámetros clave para el análisis y la relevancia de las diferentes métricas para describir la sostenibilidad (Lempert et al., 2003; Marchau et al., 2019). En este sentido, el uso de métodos de análisis computacionales ha generado una ventana de oportunidad para generar instrumentos de análisis exploratorio para incrementar las capacidades de gestión de sistemas acoplados o SSEs.

1.2. Instrumento de política para el aprovechamiento sostenible de flora y fauna en México: El caso del borrego cimarrón (Ovis canadensis)

El aprovechamiento sostenible de flora y fauna silvestre está determinado por la relación entre componentes socioeconómicos y ecológicos que conforman un socio-ecosistema. En México, existen esfuerzos importantes por impulsar un uso sostenible de las especies de flora y fauna silvestres (Carabias et al., 2010), principalmente porque se considera una estrategia de diversificación productiva de los hogares rurales (Avila-Foucat & Pérez-Campuzano, 2015) y a que estas especies ocupan un lugar muy importante en la economía de estos hogares (López-Feldman & Wilen, 2008). En el norte del país se encuentra la ganadería diversificada que nace en la década de los 60's. Se denomina ganadería diversificada, a la rama de la ganadería, que además de estar orientada a la producción de ganado, se ha diversificado al aprovechamiento sostenible de fauna silvestre, principalmente a través de la prestación de servicios de caza deportiva (Villarreal, 2012). En el estado de Baja California Sur, el aprovechamiento del borrego cimarrón es de gran importancia tanto ecológica como económica para los ejidos. Con esta actividad económica se genera un vínculo de codependencia entre los ejidatarios y la especie aprovechada.

La cacería deportiva del borrego cimarrón en México se desarrolla bajo un instrumento de política para la conservación y manejo de especies de flora y fauna denominado Unidades para la Conservación, Manejo y Uso Sostenible de la Vida Silvestre (UMAs). Este esquema tiene una extensión mayor que las áreas naturales protegidas (Avila-Foucat & Pérez-Campuzano, 2015) y su objetivo es generar ingresos para los administradores de las tierras comunitarias, ejidales y privadas derivados de la conservación de especies y su hábitat. Por consiguiente, el aprovechamiento del borrego cimarrón está determinado por la relación entre componentes socioeconómicos y ecológicos que conforman un socio-ecosistema.

El SSE en estudio se ha visto afectado por el cambio climático. A nivel mundial, en los últimos cien años, los seres humanos nos hemos convertido en una fuerza dominante de cambio en el planeta por lo cual va en incremento el consenso en el ámbito científico de que hemos entrado en una época geológica denominada “Antropoceno” (Steffen et al., 2011). El cambio climático es una de las consecuencias del impacto. Este fenómeno de implicaciones inciertas incide en los ecosistemas y de manera particular a la población de borrego cimarrón, lo cual genera desbalances en la relación sociedad-naturaleza. El estado de Baja California Sur ha presentado largos periodos de sequía. El período más largo ha sido de tres años continuos de sequía (2009-2011) el cual fue catalogado por la Comisión Nacional del Agua como la peor sequía en 70 años. Este periodo llevó al estado a tomar decisiones importantes como la de sacar al ganado de las zonas de agostadero donde la sequía tiene un mayor impacto en esta actividad económica. En el atlas del agua en México 2012 se reportó que en el 2011 los efectos de la sequía fueron clasificados como moderado severo y extremo en el estado de Baja California Sur, Baja California Norte, Sinaloa y Sonora (Conagua, 2012). En el caso del borrego cimarrón, al ser una especie en vida libre dentro del territorio, la toma de decisiones en cuanto al manejo y aprovechamiento de la especie ante eventos climáticos de esta naturaleza se vuelve compleja debido al grado de incertidumbre que existe sobre la trayectoria del evento climático y sus implicaciones ecológicas en el largo plazo. Existen diversos estudios que analizan el impacto del cambio climático en el borrego cimarrón y los desafíos para su manejo en vida silvestre, tanto en la movilización de sus poblaciones (Gedir et al., 2020) como en la inversión en la implementación de estrategias para garantizar fuentes de disponibilidad de agua ya sean naturales o artificiales (Whiting et al., 2012).

La estrategia de aprovechamiento actual del borrego cimarrón en México no considera el posible impacto del cambio climático. Para los ejidatarios, la conservación y aprovechamiento sostenible de la especie frente al cambio climático puede ser un esfuerzo complejo. Conforme las condiciones ambientales cambian, el paisaje en el que la especie interactúa en el presente puede ser diferente de los que podrían estar disponibles en el futuro. Hay varias formas en que el cambio climático está comenzando a afectar las especies silvestres. El aumento de temperatura y los cambios en los patrones históricos de precipitación pueden afectar directamente a las especies dependiendo de su fisiología y tolerancia a los cambios ambientales. El cambio climático también puede alterar el suministro de alimentos de una especie o su tiempo de reproducción, lo que afecta indirectamente en su prevalencia. De tal forma que, los patrones climáticos futuros probablemente tendrán un fuerte impacto en las distribuciones geográficas de las especies (García et al., 2016). Por lo tanto, preservar los ecosistemas y las especies en sus ubicaciones actuales puede ser cada vez más difícil porque el cambio climático se está convirtiendo en el mayor desafío para la conservación en el futuro (García et al., 2016). Por lo tanto, explorar estos efectos es un paso importante en el desarrollo de estrategias de manejo que pueden ayudar a las especies a sobrevivir al clima cambiante.

1.3. Los sistemas socio-ecológicos como sistemas complejos

Dado que los SSEs se encuentran en constante cambio, a menudo de maneras completamente novedosas, se requiere de estrategias de análisis y gestión que sean robustas ante la influencia de estresores sobre la dinámica de los sistemas. Además, se requiere de la exploración sobre cómo estos podrían cambiar en el futuro (Biggs et al., 2015; Levin et al., 2013). Para abordar estos objetivos es indispensable la implementación de marcos teóricos que promuevan una visión sistémica y la coevolución de disciplinas para generar nuevos métodos para comprender mejor los SSEs e informar políticas y prácticas de manejo (Bammer, 2005; Cilliers et al., 2013). Existe una gran diversidad de marcos para el análisis de los SSEs debido principalmente a la necesidad de conceptos que permitan estructurar el razonamiento interdisciplinario sobre problemas complejos en estos sistemas (Binder et al., 2013). Un marco teórico que aborda los desafíos sociales y ecológicos de manera integrada o entrelazada es la teoría de sistemas complejos (Cilliers et al., 2013). Los SSEs se definen como **sistemas adaptativos complejos** (SACs) (Cumming et al., 2005; Holling, 2001; Walker & Salt, 2012); en los que distintos componentes culturales, políticos, sociales, económicos, ecológicos, tecnológicos, entre otros, están interactuando(Resilience Alliance, 2015). Los sistemas también se pueden conectar o anidar con otros a través de relaciones jerárquicas a diferentes escalas (Levin, 1998). Estas interacciones entre sistemas permiten a los SACs auto organizarse y producir patrones de comportamiento adaptativos, dinámicos y emergentes (Folke, 2006).

Conceptos dentro de la literatura de los SACs como umbrales, puntos de inflexión, cambios de régimen(Folke et al., 2011; Hughes et al., 2013; Scheffer & Carpenter, 2003; Westley et al., 2011), bucles de retroalimentación y las no linealidades(Biggs et al., 2012;

Gunderson & Holling, 2002; Walker et al., 2006) se utilizan ampliamente para identificar y explicar la naturaleza compleja y los patrones del comportamiento de SSEs. Algunos otros conceptos o atributos relacionados con SSEs son, resiliencia, adaptabilidad, transformabilidad y gestión. Estos se basan en las características y dinámicas que definen las trayectorias futuras de un SSE (Folke et al., 2004, 2016; Levin et al., 2013; Walker & Salt, 2006)han dado forma a los métodos en el campo de la investigación en SSEs. Particularmente, informan de manera sustancial el enfoque de resiliencia en SSEs (Folke et al., 2016), ampliamente utilizado para comprender cómo se dirige el cambio, la adaptación y la transformación en estos sistemas. Este enfoque se ha convertido en un importante campo de investigación para comprender las relaciones y retroalimentaciones que dan forma a la dinámica y las características de los SSEs (Carpenter et al., 2005; Fischer et al., 2015) frente a estresores.

Este trabajo de investigación analiza la **resiliencia específica** del sistema de aprovechamiento del borrego cimarrón en Baja California Sur frente a los cambios en las condiciones climáticas en la región. El concepto de resiliencia que adoptamos en este trabajo es la capacidad de un sistema para adaptarse y/o transformarse ante una perturbación y seguir funcionando de forma similar (Walker et al., 2004). Esta capacidad está estrechamente relacionada con la capacidad adaptativa y la disponibilidad. La capacidad adaptativa se entiende como la capacidad para reorganizarse y reconfigurarse según sea necesario para hacer frente a las perturbaciones sin perder la capacidad funcional y la identidad del sistema. Se refiere a la presencia de una variedad de opciones de respuesta, así como a la capacidad de aprender, colaborar, adaptarse y crear nuevas estrategias para garantizar la funcionalidad. La disponibilidad se refiere a qué tan rápido puede responder un sistema frente a las condiciones cambiantes. Este atributo generalmente se ve afectado por las barreras físicas, organizativas, sociales, psicológicas u otras, internas o externas, que pueden impedir la respuesta oportuna.

El enfoque de **resiliencia** implica dos aspectos; **resiliencia especifica** como la resiliencia de una parte específica de un sistema, relacionada con una variable de control particular a uno o más tipos de estresores identificados (Folke et al., 2010). Esta resiliencia "de qué y a qué", exige identificar umbrales particulares en el sistema, más allá de los cuales comienza a funcionar de una manera diferente, impactando en la funcionalidad del sistema (S. Carpenter et al., 2001). Por otro lado, la **resiliencia general** es la resiliencia del sistema en su conjunto a todo tipo de perturbaciones (Folke et al., 2010). Abordar la resiliencia general en un sistema implica centrarse en condiciones del sistema, como la diversidad, la modularidad, la apertura, las reservas, retroalimentaciones, la anidación, el monitoreo, el liderazgo y la confianza (Carpenter et al., 2012). Así mismo en términos de gestión de resiliencia, (Biggs et al., 2015) proponen principios para construir resiliencia en SSEs ante el cambio: 1) mantener la diversidad y la redundancia; 2) gestionar la conectividad; 3) gestionar variables lentas y retroalimentaciones; 4) pensamiento adaptativo; 5) fomentar el aprendizaje; 6) ampliar la participación; y 7) promover la gobernanza policéntrica.

En las últimas décadas se han incrementado los estudios utilizando el enfoque de resiliencia en SSEs, lo cual ha enriquecido el entendimiento empírico de los mismo (Schlüter et al., 2019), sin embargo, existen algunos temas que falta desarrollar, tales como la exploración de las implicaciones de políticas en lugares particulares (Wiek et al., 2011); prestar mayor atención y explorar los umbrales socio-ecológicos los cuales generalmente se identifican cuando el sistema ya ha cruzado un umbral y colapsa s (Cumming & Peterson, 2017) (Cumming, 2011). Particularmente con el objetivo de explorar y explicar fenómenos socio-ecológicos como una forma de potenciar los objetivos de la sostenibilidad y sus esfuerzos orientados a las respuestas sociales en la solución de problemas socio-ecológicos.

1.4. Métodos numéricos para el análisis de los sistemas complejos

La implementación de modelos numéricos ha figurado como una estrategia metodológica que se considera importante para abordar SACs. Estos modelos se consideran "laboratorios virtuales" que facilitan la experimentación computacional de un SSE en situaciones donde no es posible realizar en campo experimentos de políticas (Seppelt et al., 2009). Se centran en algunos aspectos, a menudo hipotéticos, de una situación problemática compleja como primer paso para mejorar la comprensión del comportamiento de un sistema. Son particularmente útiles en situaciones en las que el conocimiento de los parámetros es limitado o cuando la disponibilidad de datos en el tiempo también es limitada. De tal forma que ayudan en la exploración de estrategias en términos de política o para desarrollar prototipos de modelos que generan hipótesis, las cuales pueden ser probadas en modelos estructuralmente más elaborados (Müller et al., 2013). Además, estos modelos también pueden servir como herramientas para la comunicación e integración de diferentes bases conceptuales y perspectivas, y como base para el desarrollo de estrategias de gestión (Daw et al., 2015).

Una forma de modelación ampliamente utilizada es la dinámica de sistemas (DS) (Ding & Nunes, 2014). En general este tipo de modelación se basa en representar el comportamiento macro del sistema a diferencia de otros como la modelación de agentes que se enfocan en la dinámica a nivel micro de los agentes que toman decisiones en el sistema (Ding et al., 2018). La DS se enfoca en la representación de las estructuras de retroalimentación y la no linealidad (Forrester, 1994)con el objetivo de visualizar, analizar y entender retroalimentaciones dinámicas complejas. Emplea herramientas para desarrollar diagramas tales como los diagramas causales y los de flujo, los cuales capturan la estructura de un sistema complejo y muestran como el sistema se encuentra dinámicamente influenciado por las interacciones de todas las variables (Abbot & Hadžikadić, 2016). Como una forma de incorporar realismo a la interacción del componente climático en el SSE, se propuso la incorporación de un modelo de nicho ecológico, el cual explora los efectos del cambio climático en la población de borrego cimarrón en Baja California Sur. Por su parte el modelo dinámico incorpora las interacciones con el componente socioeconómico del SSE.

Aunque tradicionalmente en la DS durante el proceso de la construcción del modelo/diagrama mental no se consulta con los agentes del sistema, este estudio si emplea información derivada de entrevistas semiestructuradas y encuestas a los ejidatarios que manejan el recurso y a expertos en el área del aprovechamiento de borrego cimarrón en México y en USA. Esto con el objetivo de mejorar el entendimiento sistémico y la percepción de la problemática de acuerdo a estos agentes, de tal forma que fuera posible identificar las disyuntivas en términos de manejo sostenible, además de facilitar la exploración de probables consecuencias socio-ecológicas asociadas al actual esquema de aprovechamiento del borrego cimarrón y también incentivar la coproducción de un modelo que defina el problema prioritario de acuerdo a la diversidad de visiones de los agentes en el SSE.

1.5. Preguntas de investigación

Los sistemas de aprovechamiento son SSEs complejos que enfrentan incertidumbre. Dado que la toma de decisiones para la gestión de estos sistemas es indispensable, es importante identificar las fuentes de incertidumbre para orientar la toma de decisiones hacia la sostenibilidad ecológica y socioeconómica de estos sistemas. Dada la incertidumbre asociada al cambio climático, el presente estudio se planteó las siguientes preguntas de investigación:

- ¿Cuáles son los componentes y relaciones que definen al sistema de aprovechamiento del borrego cimarrón en México?
- ¿Cuáles son los umbrales (socioeconómico y ecológico) del sistema de aprovechamiento del borrego cimarrón dentro de los cuales se debe gestionar la resiliencia socio-ecológica en el contexto del cambio climático?
- ¿Cuál es la aptitud del hábitat del borrego cimarrón en México, en la cual es posible llevar a cabo su aprovechamiento frente al cambio climático?

I.6. Objetivos

El objetivo que se planteó el presente estudio fue el de ayudar a informar sobre las implicaciones socio-ecológicas del cambio climático en la sostenibilidad y la resiliencia del sistema de aprovechamiento del borrego cimarrón en México. Para alcanzar este objetivo, el análisis se enfocó en un caso de estudio, el de la UMA ejido Alfredo Vladimir Bonfil en el estado de Baja California Sur. Para ello se plantearon los siguientes objetivos particulares:

- Desarrollar un diagrama causal del sistema de aprovechamiento del borrego cimarrón:
    - Identificar variables (componentes) socioeconómicos y ecológicos del sistema
    - Identificar relaciones de retroalimentación entre variables

- Desarrollar un modelo de simulación dinámico para identificar los umbrales socioeconómicos y ecológicos del SSE frente al cambio climático:
    - Formalizar el problema de gestión del SSE frente al cambio climático: Identificación de variables en un diagrama causal y un diagrama de flujo
    - Operacionalizar el SSE: Identificar y/o estimar parámetros de las variables del SSE)
    - Implementación del modelo del SSE en una plataforma analítica: Desarrollar un modelo computacional
    - Identificar desafíos y oportunidades para mejorar la actual política de aprovechamiento del borrego cimarrón.
- Desarrollar un modelo de aptitud del hábitat del borrego cimarrón en México:
    - Identificar desafíos y oportunidades del cambio climático para la conservación y aprovechamiento de la especie en México.

Este trabajo de investigación emplea un enfoque de resiliencia específica en SSEs para abordar un problema o estresor (Biggs et al., 2012; Folke et al., 2010), utilizando como método de modelación el enfoque de DS, el cual se complementó con la modelación de nicho ecológico para alcanzar un mejor entendimiento del problema (cambio climático) en la gestión del sistema de aprovechamiento del borrego cimarrón en México.

El **capítulo 1** desarrolla conceptos teórico-metodológicos que dan sustento a los capítulos 2 y 3 desarrollados en formato de artículos. Este primer capítulo también hace mención a la importancia de incluir la perspectiva de análisis de política para analizar desafíos y oportunidades para alcanzar la sostenibilidad de SSEs y gestionar la resiliencia a través de políticas adaptativas. El **capítulo 2** es el artículo de requisito publicado en una revista indizada. Este artículo emplea un caso de estudio para el desarrollo de un modelo de simulación computacional como herramienta de análisis para explorar desafíos y oportunidades de la política actual en el aprovechamiento del borrego cimarrón y para identificar los umbrales de la resiliencia del SSE. Este caso de estudio permitió explorar cuantitativamente cómo la implementación de estrategias de manejo/políticas adaptativas permiten gestionar la resiliencia del SSEs para la sostenibilidad frente al cambio climático. El **capítulo 3** se trata del artículo (versión borrador final) que hace un análisis sobre la aptitud del hábitat del borrego cimarrón en México frente al cambio climático y permite identificar posibles desafíos para la conservación y aprovechamiento de la especie en México.

La importancia de este estudio radica en abordar el concepto de interdependencia como un componente central en un marco de toma de decisiones que informa sobre las intervenciones de gestión con un enfoque de sostenibilidad. Así mismo, se basa en el enfoque de resiliencia específica para incidir en la planificación del aprovechamiento del borrego cimarrón, centrándose en mejorar nuestra comprensión sobre la dinámica socio-ecológica y sobre la identificación de aspectos críticos o umbrales para mantener el aprovechamiento sostenible de la especie.

II. CAPÍTULO 1

Desafíos y oportunidades para la sostenibilidad de SSEs frente al cambio climático: Políticas, Resiliencia y Adaptabilidad

En el discurso público, se ha generado una mayor toma de conciencia por parte de la sociedad sobre la importancia de alcanzar el desarrollo sostenible, lo que ha dado lugar a un notable incremento de las presiones a favor de la puesta en marcha de acciones conducentes al logro de dicho objetivo. Los pilares de este discurso (Informe Brundtland, 1987; PNUMA, 1991) lo ven materializado en la cumbre de Río, 1992 (surge la agenda 21) la cual supuso un punto de inflexión en la actuación de los gobiernos en materia de protección y conservación del sistema natural. A partir de ese momento, el desarrollo sostenible comienza a considerarse un objetivo prioritario a alcanzar por las políticas tanto a nivel nacional como internacional (Costa, 2000). Se hace énfasis en que, para hacer frente a los desafíos del desarrollo sostenible frente al cambio climático, el interés público a través de las políticas debe poner en marcha estrategias adaptativas enfocadas en la sostenibilidad de los sistemas socio-ecológicos (SSEs), las cuales se ajusten con el tiempo a la luz de nueva información (IPCC, 2021a), esto como una forma de atender la incertidumbre asociada a las formas en que el cambio climático pueda desplegarse a escala regional o local. Este desarrolla un conjunto de conceptos teórico-metodológicos, los cuales son el antecedente de los capítulos 2 y 3 desarrollados en formato de artículo científico.

1.1 Perspectiva de política en la sostenibilidad de los SSEs

A medida que los responsables de la formulación de políticas y los científicos naturales se ven presionados por abordar cuestiones de sostenibilidad, se reconoce la necesidad de la colaboración de científicos sociales, naturales y responsables de la formulación de políticas para tener un impacto sólido y eficaz, en particular para influir en las políticas (Oliver & Cairney, 2019). El marco del “análisis de políticas” es un enfoque para comprender y guiar la elección de políticas y estrategias para ponerlas en práctica (Mayer et al., 2004).

Desde la perspectiva de análisis de política, diversos instrumentos analíticos se pueden adoptar (Meltzer & Schwartz, 2019). Las fases del análisis de política (definición del problema, diseño de la política, implementación de la política, monitoreo y evaluación) son un elemento valioso para investigar la congruencia de las políticas sobre los objetivos socio-ecológicos. En términos generales, quienes formulan las políticas tendrían que definir su agenda incluyendo a las implicaciones socio-ecológicas. De esta forma, la toma de decisiones estaría siendo informada con evaluaciones sobre el estado de los socio-ecosistemas. Al mismo tiempo, las retroalimentaciones de la política tomarían en cuenta consecuencias positivas y negativas para los mismos socio-ecosistemas. Los elementos distintivos del marco de análisis de políticas es que se enfocan en los siguientes compromisos analíticos:

- *Orientación a problemas*

El punto de partida del análisis es abordar un problema de importancia normativa. Para mejorar la sostenibilidad, este se considera un punto de partida obligado (OECD, 2010). La definición del problema es un ejercicio, es una combinación de establecer qué valores están en juego y trazar diagnósticos potenciales de las raíces del problema. Por lo tanto, la definición del problema es tanto un esfuerzo normativo como analítico. La amplitud y profundidad de la definición del problema indican si se ha realizado un esfuerzo serio. El analista debe ser consciente de que cada situación tiene valores en juego y debe aclarar los valores de los distintos actores, así como los propios del investigador.

Las dimensiones de los requisitos de la sostenibilidad son: mantener cierto grado de funcionamiento del ecosistema, incidir en el comportamiento humano y encontrar adaptaciones a las tendencias biofísicas (Galvani et al., 2016; Milner-Gulland, 2012). Juzgar qué aspectos del funcionamiento de los ecosistemas son relevantes inevitablemente requiere un análisis de los valores que se deben otorgar. La necesidad de capturar valores relevantes se refleja en el surgimiento del concepto de "triple resultado" donde, la productividad económica, la protección ambiental y la integridad sociocultural son igual de importantes (García et al., 2016; Kengar et al., 2021).

De esta manera, una definición de problema deficiente o incompleta puede conducir fácilmente a políticas que, al perseguir un conjunto de objetivos, pueden poner en peligro otros objetivos que son importantes para la sostenibilidad. Por lo tanto, las definiciones de problemas deben ser integradoras. La perspectiva de análisis de política puede ayudar a orientar esta sucesión. El mapeo de valores y perspectivas aporta elementos importantes sobre cómo profundizar en la definición del problema.

- *Mapeo de valores*

La definición convencional del "problema que enfrenta la sostenibilidad" es el comportamiento económico irresponsable de personas que no aprecian o no se preocupan por la conservación y las consecuencias ambientales de sus acciones. A menudo, la compensación entre las demandas económicas y las preocupaciones ambientales se materializa en una suposición de que la economía y el ecosistema están intrínsecamente en desacuerdo. Sin embargo, existen beneficios económicos del enfoque de conservación (ecoturismo, agricultura orgánica, entre otros) y, lo que es más importante, que la sostenibilidad económica a largo plazo también está en riesgo debido a acciones que degradan a los ecosistemas. Al respecto, el esfuerzo de la Comisión Mundial sobre el Medio Ambiente y el Desarrollo (Comisión Brundtland[2]) se refleja en haber ampliado la definición de sostenibilidad para abarcar toda la gama de valores humanos ("el desarrollo sostenible que satisface las necesidades del presente sin comprometer la capacidad de las generaciones futuras para satisfacer sus propias necesidades"). Al respecto, se reconoce que no es solo una disyuntiva entre los valores (la riqueza frente al bienestar y el respeto por la naturaleza asociado con un ecosistema menos degradado), sino también es una disyuntiva temporal entre las ganancias económicas a corto plazo y las preocupaciones tanto económicas como ambientales a largo plazo.

[2] Comisión mundial creada en 1987 para el desarrollo del medio ambiente, presidida por la ex primera ministra de Noruega Gro Harlem Brundtland, a cuyos trabajos se debe la definición comúnmente aceptada de desarrollo sostenible: "Aquél capaz de satisfacer las necesidades del presente sin comprometer el derecho de las generaciones futuras para satisfacer las suyas propias"

- *Mapeo de perspectivas*

Las personas en circunstancias particulares carecen de identificación con las generaciones futuras. Además, también suelen defender un conjunto limitado de metas, aparentemente sin comprender que una disminución en otras categorías de valores pondría en peligro el logro del conjunto limitado de metas que tienen. Por ejemplo, si la búsqueda de la riqueza conduce a una tala muy excesiva (Larson & Ribot, 2007), el declive del sector forestal amenazará los beneficios económicos y los ecosistemas. Este ejemplo, tienen una dimensión temporal, que es crucial para los temas de sostenibilidad. La razón más comentada en términos de sostenibilidad es el desafío de preservar las oportunidades a largo plazo frente a los beneficios a corto plazo. Pero más allá de eso, un problema temporal más sutil es que muchos procesos de políticas están orientados a buscar una solución inmediata ahora para un desafío a largo plazo. No se trata simplemente de una cuestión de tranquilidad, sino también del crédito político que se podría obtener al resolver problemas graves. Por ejemplo, los debates sobre el cambio climático global se han centrado en gran medida en llegar a acuerdos para "resolver" el problema del calentamiento global derivado de la emisión de gases de efecto invernadero. Al respecto, el Panel Intergubernamental sobre Cambio Climático advierte que "el desafío no es encontrar la mejor política hoy para los próximos 100 años, sino seleccionar una estrategia prudente y ajustarla con el tiempo a la luz de nueva información" (IPCC, 2021a)

1.2.Proceso de formulación de políticas

El énfasis del marco de análisis de políticas en los mismos procesos de su formulación conecta los resultados de las políticas que dan forma al comportamiento de un sistema con las instituciones y los procesos que generan determinados resultados. La premisa es que la forma en que se hacen las políticas marca la diferencia en los resultados de estas. Por lo tanto, mientras que muchas definiciones de problemas se enfocan en identificar políticas subóptimas, otro enfoque de profundización es enfocarse en los procesos subóptimos que producen estas políticas. Por lo tanto, las alternativas para las políticas deficientes a menudo radican en mejorar el proceso de formulación de las políticas (identificación del problema) (Head & Alford, 2015). Adicionalmente, el proceso de formulación de políticas nos lleva a tratar el proceso de la integración del conocimiento para su formulación. La integración entre disciplinas ha recibido probablemente la mayor atención y parece la más obvia para los observadores, porque la formulación de las mejores políticas para promover la sostenibilidad requiere conectar las ciencias biofísicas y sociales y, además, requiere examinar la gama de valores que motivan el comportamiento humano. Sin embargo, las continuas llamadas a la colaboración interdisciplinaria, multidisciplinaria y transdisciplinaria son una señal de que dicha colaboración es técnicamente difícil y aún va en contra de los enfoques analíticos en muchos campos del conocimiento (Brewer, 1999).

Un aspecto particularmente difícil de la integración entre disciplinas es el desafío de equilibrar la información cuantitativa y cualitativa. En este sentido, el marco del análisis de política no privilegia la investigación cuantitativa ni cualitativa, y en su evaluación (se reconoce el papel del conocimiento en el proceso de toma de decisiones), requiere aportaciones de conocimiento integrales para la toma de decisiones (Meltzer & Schwartz, 2019).

Con respecto del conocimiento acumulado en temas de sostenibilidad también se puede mencionar la transferencia de conocimiento acumulado. Si se llevara a cabo, un esfuerzo analítico para catalogar el conocimiento acumulado sobre las estrategias para promover la sostenibilidad éste podría revelar que, una enorme cantidad de conocimiento sobre los esfuerzos exitosos y no exitosos pasa desapercibida para las personas que abordan los desafíos dentro de sus propios contextos específicos. Esto se debe en parte a las limitaciones de la comunicación de casos entre una región, nación o incluso de una región del mundo a otra, y en parte también a las dificultades para ajustar y adaptar las experiencias y aprendizajes de un contexto a otro (van Mierlo & Beers, 2020). En este sentido, el marco de análisis de políticas ha desarrollado las herramientas de análisis funcional. De esta forma gran parte de la dificultad de comparar casos en diferentes contextos puede superarse (Ordoñez-Matamoros, 2013). Por ejemplo, el hecho de que la institución que moviliza la acción ambiental en un país sea una agencia gubernamental y en otro sea una red de organizaciones no gubernamentales (ONG) no disminuye la posibilidad de que las estrategias exitosas utilizadas en el primero puedan emplearse en el segundo, ya que siempre que el análisis tenga en cuenta las diferencias institucionales y contextuales específicas será posible rescatar los elementos asequibles. En otros contextos como en la gestión de recursos hídricos, se ha señalado la necesidad de generar una comunidad de prácticas en la cual, los organismos encargados de la gestión del recurso compartan las experiencias enfocadas al desarrollo de mejores prácticas para la sostenibilidad (Maida & Beck, 2018).

1.3. Adaptabilidad y resiliencia en la gestión de SSEs ante el cambio climático: Sistemas de aprovechamiento de especies de vida silvestre

Las cláusulas de objetos o las políticas e instrumentos de planificación en materia de conservación y aprovechamiento de especies de vida silvestre estipulan los factores que los responsables de la toma de decisiones deben tener en cuenta y establecen el marco amplio dentro del cual se desarrollan e implementan otras políticas y planes. Cambiar los objetos estatutarios y los principios de toma de decisiones en los regímenes regulatorios ambientales pueden brindar orientación a los tomadores de decisiones sobre la importancia de la flexibilidad y la capacidad de respuesta en condiciones de incertidumbre.

El supuesto subyacente de muchos regímenes de gestión ambiental y de recursos es que los sistemas naturales son estacionarios y que el cambio se produce dentro de una "variabilidad" fija, por lo tanto, el estatus quo debe protegerse, preservarse o mantenerse. La "estabilidad" de los sistemas naturales que sustenta el modelo de conservación preservacionista[3] que busca mantener las condiciones basadas en una línea de base preconcebida es poco realista incluso en ausencia del cambio climático, sin embargo, los impactos del cambio climático hacen que incluso la preservación sea ecológicamente desafiante. Aunque no se admita abiertamente en el ámbito político que la pérdida de biodiversidad y el cambio del ecosistema son inevitables, el objetivo de la conservación debe revisarse. Al menos, se debe incluir la promoción de la resiliencia y la capacidad de adaptación, y la protección de los servicios ecosistémicos críticos. Sin embargo, cuando es un hecho que los impactos del cambio climático son y serán graves, es muy probable que

[3] La corriente denominada preservacionista centra su posición en la conservación integral de la biosfera: ningún aspecto constitutivo de la biosfera debe ser tocado por las actividades del hombre, salvo en caso de urgencia. El hombre no posee ningún derecho sobre los recursos naturales (Pérez, 2011)

los objetivos deban ir más allá y adoptar un enfoque orientado hacia la minimización de daños y la prevención del colapso de los sistemas socio-ecológicos.

En la práctica, los objetivos de gestión podrían incluir un requisito explícito de planificación vinculado a los impactos del cambio climático y el reconocimiento de la importancia de la resiliencia y la capacidad de adaptación como metas estatutarias. Esto daría a los tomadores de decisiones una amplia discreción para determinar los marcos de tiempo sobre los cuales se podrían considerar los impactos y la extensión y la manera en que se debería permitir que esos impactos proyectados alteren los objetivos y enfoques de gestión más tradicionales. Alternativamente, los objetivos de gestión de recursos específicos podrían modificarse para reflejar la necesidad de objetivos más centrados en la resiliencia, a la luz de los impactos del cambio climático.

Un elemento importante en el desarrollo de políticas para la sostenibilidad de los SSEs es impulsar la capacidad de adaptación a través del ***manejo adaptativo*** como estrategia. El término "manejo adaptativo" describe una nueva forma de abordar la evaluación y el manejo ambiental. Refleja el cambio de paradigma en la biología de la conservación que adoptó una visión dinámica y no estacionaria de los sistemas naturales (Allen & Garmestani, 2015). El manejo adaptativo es un enfoque interdisciplinario (Dreiss et al., 2017) dado que reconoce a la incertidumbre como inherente a los sistemas naturales, y que los factores ecológicos, sociales y económicos deben integrarse plenamente en las primeras etapas del proceso de toma de decisiones. La gestión adaptativa reconoció las limitaciones de la ciencia para hacer predicciones precisas sobre los impactos ambientales futuros e identifica el peso de las decisiones como una debilidad crítica porque significa que las decisiones de gestión y reglas se basan casi inevitablemente sobre información incompleta (Murray & Marmorek, 2003). La gestión adaptativa también reconceptualizó la toma de decisiones como cíclica en lugar de lineal, para permitir la revisión, modificación e inversión económica adicional basada en nueva información y cambios inesperados (Murray & Marmorek, 2003).

La gestión adaptativa se ha adoptado en varios contextos a nivel global para informar en la gestión de sistemas ecológicos o socio-ecológicos de gran escala y complejos donde las decisiones de gestión no pueden esperar a los resultados finales de la investigación (Murray & Marmorek, 2003; Williams & Brown, 2014). Este enfoque se concibe como un método de aprendizaje continuo (Williams & Brown, 2014). Sin embrago, Duncan & Wintle (2008) identifican dos variantes: 1) gestión de prueba y error y 2) gestión adaptativa pasiva o activa. La gestión de prueba y error comúnmente implica persistir con la opción de gestión que se considera la mejor en ese momento hasta que se demuestre que es inadecuada, momento en el cual las acciones de manejo pueden cambiarse con la esperanza de lograr un mejor resultado. Este tipo de gestión no está respaldada por un modelo formal para el sistema que se está gestionando, no reconoce explícitamente la incertidumbre en la gestión, no implica un plan de aprendizaje, y por lo general no se replica, por lo que se considera estadísticamente no riguroso. En contraste, el manejo adaptativo pasivo reconoce explícitamente la incertidumbre acerca de cómo las acciones de manejo contribuyen a los resultados de la gestión y usualmente involucra la aplicación concurrente de opciones de manejo para que el aprendizaje sobre el sistema y la eficacia relativa de la gestión pueda lograrse a medida que avanza el proceso. El aprendizaje debe basarse en una evaluación formal de la evidencia, preferiblemente respaldada por inferencias estadísticas. El manejo adaptativo activo implica un programa de aprendizaje sobre la eficacia de las opciones de gestión. Este enfoque tiene como objetivo maximizar las ganancias a largo plazo a través de una asignación estratégica de recursos para la gestión y el aprendizaje, a veces a expensas de las ganancias a corto plazo. Por consiguiente, la formulación precisa y el enfoque de la gestión adaptativa serán producto del contexto, la gestión del sistema, las metas, los recursos, y la calidad de la información disponible. De acuerdo con algunos autores, desde el enfoque de manejo adaptativo, la estrategia económica como motor para la continuidad de la estrategia de gestión en el largo plazo sigue siendo un desafío (Scarlett, 2013; Williams & Brown, 2016)

Por su parte la ***Adaptación basada en Ecosistemas*** (AbE) o ***Gestión basada en Ecosistemas*** es una combinación de políticas que incluye instrumentos y herramientas de políticas típicos relacionados con Biodiversidad y Servicios Ecosistémicos (BES), pero también políticas socioeconómicas relacionadas con el desarrollo. Para ajustarse al marco de AbE, los instrumentos de política típicos de la agenda de conservación de la biodiversidad (por ejemplo, establecimiento y manejo efectivo de áreas protegidas, manejo comunitario de áreas naturales, restauración ecológica, y otros) serán parte de una combinación que incluye mecanismos y políticas – atención a problemas de generación de ingresos, reducción de la pobreza y / o desarrollo de infraestructura, y mitigación del carbono–. Por lo tanto, esta combinación de políticas se plantea como una estrategia que reducirá la vulnerabilidad social y se adaptará al cambio climático (O'Higgins et al., 2020).

Es un hecho que el cambio climático aumenta la incertidumbre y el dinamismo de los ecosistemas y los recursos y exacerba los factores de estrés existentes. De esta manera, la premisa de la previsibilidad de los cambios sociales y ecosistémicos a largo plazo es baja, y sostiene la importancia de un marco de análisis para abordar los cambios a futuro y lograr una mejor comunicación entre ciencia y sociedad, de tal forma que se puedan identificar las áreas de incidencia de las políticas para abordar los principales desafíos para la sostenibilidad y la resiliencia socio-ecológica.

1.4. Métodos computacionales para la gestión de la sostenibilidad de los SSEs frente al cambio climático.

La combinación de ambas condiciones, complejidad e incertidumbre profunda ha complicado el papel de los métodos de análisis de política tradicional cuando se aplican a los desafíos de la sostenibilidad. Por un lado, el uso de modelos simplistas para el análisis puede resultar en omisiones relevantes para determinar los resultados a largo plazo. Por otro lado, si el alcance de un análisis es demasiado estrecho, es difícil hacer que el análisis sea relevante para una amplia gama de actores (Lempert et al., 2003; Marchau et al., 2019). Por lo tanto, la pregunta emergente en las ciencias de la sostenibilidad es cómo diseñar intervenciones políticas sólidas que tengan en cuenta explícitamente la complejidad e incertidumbre profunda y que pueda informar con detalles prácticos discusiones de política sobre los desafíos de sostenibilidad que afectan a una amplia gama de actores. Herramientas de inteligencia computacional, como aprendizaje de máquina, modelos de optimización, modelado dinámico y visualización de datos, ofrecen oportunidades para eludir estas limitaciones (Bryant & Lempert, 2010; Groves & Lempert, 2007; Isley et al., 2015; Kasprzyk et al., 2013; Kwakkel, 2017; Lempert et al., 2006). Sin embargo, su poder analítico para las ciencias de la sostenibilidad puede aprovecharse mejor cuando se utilizan en una forma integrada. Por ejemplo, modelos de simulación complejos, como los modelos de dinámica de sistemas (DS), modelos basados en agentes (ABM), se pueden utilizar como generadores de escenarios en contextos de simulación exploratoria.

Además, las técnicas de optimización multiobjetivo y de propósito general se pueden combinar con los modelos DS, ABM para estimar la respuesta óptima de políticas a través de grandes conjuntos de parametrizaciones factibles. La base de datos resultante se puede analizar más a fondo con algoritmos de aprendizaje de máquina para clasificar los resultados en términos de la combinación de valores de parámetros que desencadenan diferentes políticas. Finalmente, las técnicas interactivas de visualización de datos se pueden utilizar para crear herramientas de apoyo a la toma de decisiones para los actores y el público en general (Molina-Perez et al., 2020).

Durante las últimas dos décadas, un creciente cuerpo de investigación ha aplicado este enfoque integrador para estudiar varios desafíos de sostenibilidad en el contexto de la gestión del agua (Groves et al., 2019; R. J. Lempert & Groves, 2010; Molina-Perez et al., 2019), la energía (Popper et al., 2009) y la planificación de recursos naturales (Fischbach et al., 2019; Groves et al., 2016). Los hallazgos de estos estudios demuestran que no existen soluciones mágicas para lograr la sostenibilidad en los subsistemas humano y ecológico y que las políticas que pueden contribuir a lograr los resultados con frecuencia se basan en combinaciones de diferentes medidas que deben implementarse secuencialmente. Primero, abordando las vulnerabilidades inmediatas a través de políticas. En segundo lugar, respondiendo adaptativamente al medio y cambios a largo plazo en ambos subsistemas o esferas (Groves et al., 2019; Molina-Perez et al., 2019) para gestionar las capacidades de resiliencia de los SES. Este enfoque se define como toma de decisiones bajo condiciones de incertidumbre profunda (DMDU por sus siglas en inglés) (Marchau et al., 2019) la cual se considera que ha cimentado las bases para la aplicación general de herramientas de inteligencia computacional para las ciencias de la sostenibilidad (Groves et al., 2016).

El desarrollo de estrategias para la gestión de los SSE es indispensable para alcanzar su sostenibilidad. Por su parte, el MA se ha señalado como un en foque indispensable para alcanzar este objetivo. Sin embargo, uno de los desafíos identificados para implementar el MA es el financiamiento adecuado, dado que las estrategias adaptativas requieren aumentos proporcionales en los recursos de los actores responsables para desarrollarlas y hacerlas cumplir (recopilación de datos, seguimiento, evaluación y ajuste -técnico, económico- de planes o proyectos) (Scarlett, 2013; Williams & Brown, 2016). Por otro lado, el enfoque de AbE, se enfoca en una combinación de políticas que incluye instrumentos y herramientas de políticas típicos relacionados con las medidas de gestión de Biodiversidad y Servicios Ecosistémicos (BSE), pero también políticas socioeconómicas relacionadas con el desarrollo. Sin embargo, su aplicación aun está en la etapa de experimentación. Para ambos enfoques (MA y AbE), el análisis de políticas supone un elemento básico para su implementación. En este sentido el enfoque de DMDU es un conjunto de herramientas analíticas que se ha implementado en la gestión de la sostenibilidad y resiliencia de largo plazo en varios contextos gracias al uso de modelos de simulación, técnicas estadísticas y el uso de capacidad de cómputo para generar una gran diversidad de posibles trayectorias -y analizar sus tendencias- y por lo tanto generar, un análisis robusto de las políticas en el largo plazo.

Referencias

Abbot, R., & Hadžikadić, M. (2016). *Complex Adaptive Systems, Systems Thinking, and Agent-Based Modeling*. SpringerLink.

Adger, W. (2000). Social and Ecological resilience, are they related? *Progress in Human Geography*, *24*, 346–364. https://doi.org/10.1191/030913200701540465

Adger, W. N. (2010). Social Capital, Collective Action, and Adaptation to Climate Change 1. *Economic Geography*.

Advani, N. (2014). *Climate Change Vulnerability Assessment for Species*. https://doi.org/10.13140/RG.2.1.3613.5522

Allen, C. R., & Garmestani, A. S. (2015). *Adaptive Management of Social-Ecological Systems*. . SpringerLink.

Allouche, O., Tsoar, A., & Kadmon, R. (2006). Assessing the accuracy of species distribution models: Prevalence, kappa and the true skill statistic (TSS). *Journal of Applied Ecology*, *43*(6), 1223–1232. https://doi.org/10.1111/j.1365-2664.2006.01214.x

Alvarez-Cárdenas, S., Galina-Tessaro, P., Díaz-Castro, S., Guerrero-Cárdenas, I., Castellanos-Vera, A., Mesa-Zavala, E., Investigaciones, C. de, No, S. C. M. B., Palo, P., Rita, D. S., Paz, L., & Sur, B. C. (2009). Evaluación de elementos estructurales del hábitat del borrego cimarrón en la Sierra del Mechudo , Baja California Sur , México. *Tropical Conservation Science*, *2*(2), 189–203.

Andrew, N. (1994). *Demography and Habitat Use of Desert-Dwelling Mountain Sheep in the East Chocolate Mountains, Imperial County, California*. University of Rhode Island.

Armitage, D., Béné, C., Charles, A. T., Johnson, D., & Allison, E. H. (2012). The interplay of well-being and resilience in applying a social- ecological perspective. *Ecology and Society*, *17*(4). https://doi.org/10.5751/ES-04940-170415

Ashcroft, M. B. (2010). Identifying refugia from climate change. *Biogeography*, *37*, 1407–1413.

Avila-Foucat, V. S., & Pérez-Campuzano, E. (2015). Municipality socioeconomic characteristics and the probability of occurrence of Wildlife Management Units in Mexico. *Environmental Science and Policy*, *45*, 146–153. https://doi.org/10.1016/j.envsci.2014.08.005

Bálint, M., Domisch, S., Engelhardt, C. H. M., Haase, P., Lehrian, S., Sauer, J., Theissinger, K., Pauls, S. U., & Nowak, C. (2011). Cryptic biodiversity loss linked to global climate change. *Nature Climate Change*, *1*(6), 313–318. https://doi.org/10.1038/nclimate1191

Bammer, G. (2005). Guiding principles for integration in natural resource management (NRM) as a contribution to sustainability. *Australasian Journal of Environmental Management*, *12*(SUPPL.1), 5–7. https://doi.org/10.1080/14486563.2005.9725099

Biggs, H., Pollard, S., & Toit, D. (2015). SYSTEMIC LINKS BETWEEN SOCIETY , WETLANDS AND WOODLANDS - THE BUSHBUCKRIDGE CASE. *UNPUBLISHED*, *October*, 246–256.

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E. L., BurnSilver, S., Cundill, G., Dakos, V., Daw, T. M., Evans, L. S., Kotschy, K., Leitch, A. M., Meek, C., Quinlan, A., Raudsepp-Hearne, C., Robards, M. D., Schoon, M. L., Schultz, L., & West, P. C.

(2012). Toward Principles for Enhancing the Resilience of Ecosystem Services. *Annual Review of Environment and Resources*, *37*(1), 421–448. https://doi.org/10.1146/annurev-environ-051211-123836

Binder, C. R., Hinkel, J., Bots, P. W. G., & Pahl-Wostl, C. (2013). Comparison of frameworks for analyzing social-ecological systems. *Ecology and Society*, *18*(4). https://doi.org/10.5751/ES-05551-180426

Brewer, G. D. (1999). The Challenges of Interdisciplinarity. *Policy Sciences*, *32*(4), 327–337. https://doi.org/10.1023/A:1004706019826

Bryant, B. P., & Lempert, R. J. (2010). Thinking Inside the Box: A Participatory, Computer- Assisted Approach to Scenario Discovery. *Gical Forecasting and Social Change*, *77*(1), 34–39.

Burgos, A., & Velázquez, A. (2019). A Territory Oriented Approach to Operationilize Sustainable Management. *Global Journal of Human Social Science*, *11*.

Carabias, J., Sarukhán, J., de la Maza, J., & Galindo, C. (2010). Patrimonio Natural de México. Cien casos de éxito. In *Patrimonio natural de México. Cien casos de éxito*.

Carpenter, S. R., Arrow, K. J., Barrett, S., Biggs, R., Brock, W. A., Crépin, A. S., Engström, G., Folke, C., Hughes, T. P., Kautsky, N., Li, C. Z., Mccarney, G., Meng, K., Mäler, K. G., Polasky, S., Scheffer, M., Shogren, J., Sterner, T., Vincent, J. R., … de Zeeuw, A. (2012). General resilience to cope with extreme events. *Sustainability*, *4*(12), 3248–3259. https://doi.org/10.3390/su4123248

Carpenter, S. R., Westley, F., & Turner, M. G. (2005). Surrogates for resilience of social-ecological systems. In *Ecosystems* (Vol. 8, Issue 8, pp. 941–944). https://doi.org/10.1007/s10021-005-0170-y

Carpenter, S., Walker, B., Anderies, J. M., & Abel, N. (2001). From Metaphor to Measurement: Resilience of What to What? *Ecosystems*, *4*(8), 765–781. https://doi.org/10.1007/s10021-001-0045-9

Carpenter, Stephen., & Gunderson, Lance. (2001). Coping with Collapse: Ecological and Social Dynamics in Ecosystem Management. *BioScience*, *51*(6), 451. https://doi.org/10.1641/0006-3568(2001)051[0451:CWCEAS]2.0.CO;2

Ceballos, G., & Oliva, G. (2005). *Los mamíferos silvestres de México*. CONABIO—Fondo de Cultura Económica.

Cheung, W., Jones, M., & Lam, V. (2016). Transform high seas management to build climate resilience in marine seafood supply. *Fish and Fisheries*.

Chidumayo, Emmanuel. (2011). *Climate change and african forest and wildlife resources*. African Forest Forum.

Cilliers, P., Biggs, H. C., Blignaut, S., Choles, A. G., Jewitt, G. P. W., & Roux, D. J. (2013). Complexity , Modeling , and Natural Resource Management. *Ecology and Society*, *18*(3).

Colchero, F., Medellin, R. A., Clark, J. S., Lee, R., & Katul, G. G. (2009). Predicting population survival under future climate change: Density dependence, drought and extraction in an insular bighorn sheep. *Journal of Animal Ecology*, *78*(3), 666–673. https://doi.org/10.1111/j.1365-2656.2009.01528.x

Conagua. (2012). *Atlas del agua en México 2012*. https://doi.org/ISBN: 978-607-8246-29-8

Contreras, A., & Espinosa, A. (2010). Evaluación de hábitat para la restauración del borrego cimarrón (Ovis canadensis) en Coahuila, México. *Redalyc*, *13*(1), 78–86.

Cumming, G. S., Barnes, G., Perz, S., Schmink, M., Sieving, K. E., Southworth, J., Binford, M., Holt, R. D., Stickler, C., & van Holt, T. (2005). An exploratory framework for the empirical measurement of resilience. *Ecosystems*, *8*(8), 975–987. https://doi.org/10.1007/s10021-005-0129-z

Cumming, G. S., & Peterson, G. D. (2017). Unifying Research on Social–Ecological Resilience and Collapse. In *Trends in Ecology and Evolution* (Vol. 32, Issue 9). https://doi.org/10.1016/j.tree.2017.06.014

D'Almeida Martins, R., & da Costa Ferreira, L. (2011). Opportunities and constraints for local and subnational climate change policy in urban areas: Insights from diverse contexts. *International Journal of Global Environmental Issues*, *11*(1), 37–53. https://doi.org/10.1504/IJGENVI.2011.040250

Danell, Kjell. (2006). *Large herbivore ecology, ecosystem dynamics and conservation*. Cambridge University Press.

Daw, Coulthard, Cheung, Brown, K., Abunge, C., Galafassi, D., Peterson, G., McClanahan, T., Omukoto, O., & Munyi, L. (2015). Evaluating taboo trade-offs in ecosystems services and human well-being. *PNAS*.

DeCesare, N., & Pletscher, D. H. (2006). Movements, Connectivity, and Resource Selection of Rocky Mountain Bighorn Sheep. *Journal of Mammalogy*, *87*(3), 531–538. https://doi.org/10.1644/05-MAMM-A-259R1.1

Ding, H., & Nunes, P. (2014). Modeling the links between biodiversity , ecosystem services and human wellbeing in the context of climate change : Results from an econometric analysis of the European forest ecosystems. *Ecological Economics*, *97*, 60–73. https://doi.org/10.1016/j.ecolecon.2013.11.004

Douglas, C. L., & Leslie, D. M. (1983). Influence of Weather and Density on Lamb Survival of Desert Mountain Sheep. *He Journal of Wildlife Management* , *50*, 153–156.

Dreiss, L. M., Hessenauer, J. M., Nathan, L. R., O'Connor, K. M., Liberati, M. R., Kloster, D. P., Barclay, J. R., Vokoun, J. C., & Morzillo, A. T. (2017). Adaptive Management as an Effective Strategy: Interdisciplinary Perceptions for Natural Resources Management. *Environmental Management*, *59*(2), 218–229. https://doi.org/10.1007/s00267-016-0785-0

Dreiss, L. M., Lacey, L. M., Weber, T. C., Delach, A., Niederman, T. E., & Malcom, J. W. (2022). Targeting current species ranges and carbon stocks fails to conserve biodiversity in a changing climate: Opportunities to support climate adaptation under 30 × 30. *Environmental Research Letters*, *17*(2). https://doi.org/10.1088/1748-9326/ac4f8c

Duncan, D. H., & Wintle, B. A. (2008). Towards Adaptive Management of Native Vegetation in Regional Landscapes. In C. W. Pettit C., Bishop I., Lowell K., Pullar D., & Duncan D. (Eds.), *Landscape Analysis and Visualisation. Lecture Notes in Geoinformation and Cartography.* (pp. 160–181). https://doi.org/https://doi.org/10.1007/978-3-540-69168-6_9

Escobar-Flores, J. G., Alvarez-Cardenas, S., Valdez, R., Torres-Rodriguez, J., Díaz-Castro, S., Castellanos-Vera, A., & Martinez-Gallardo, R. (2015). Detección de las preferencias de hábitat del borrego cimarrón (Ovis canadensis cremnobates) en Baja California, mediante Técnicas de Teledetección Satelital. *Therya*, *6*(3), 519–534. https://doi.org/10.12933/therya-15-284

Fischbach, J. R., Johnson, D. R., & Groves, D. G. (2019). Flood damage reduction benefits and costs in Louisiana's 2017 coastal master plan. . *Environ. Res. Commun*.

Fischer, J., Gardner, T. A., Bennett, E. M., Balvanera, P., Biggs, R., Carpenter, S., Daw, T., Folke, C., Hill, R., Hughes, T. P., Luthe, T., Maass, M., Meacham, M., Norström, A. v., Peterson, G., Queiroz, C., Seppelt, R., Spierenburg, M., & Tenhunen, J. (2015). Advancing sustainability through mainstreaming a social-ecological systems perspective. *Current Opinion in Environmental Sustainability*, *14*, 144–149. https://doi.org/10.1016/j.cosust.2015.06.002

Folke, C. (2006). Resilience: The emergence of a perspective for social-ecological systems analyses. *Global Environmental Change*, *16*(3), 253–267. https://doi.org/10.1016/j.gloenvcha.2006.04.002

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

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2010). Resilience Thinking : Integrating Resilience , Adaptability and Transformability. *Ecology and Society*, *15*(4), 20.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., & Holling, C. S. (2004). Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology, Evolution, and Systematics*, *35*, 557–581. https://doi.org/10.1146/annurev.ecolsys.35.021103.105711

Folke, C., Jansson, Å., Rockström, J., Olsson, P., Carpenter, S. R., Stuart Chapin, F., Crépin, A. S., Daily, G., Danell, K., Ebbesson, J., Elmqvist, T., Galaz, V., Moberg, F., Nilsson, M., Österblom, H., Ostrom, E., Persson, Å., Peterson, G., Polasky, S., … Westley, F. (2011). Reconnecting to the biosphere. *Ambio*, *40*(7), 719–738. https://doi.org/10.1007/s13280-011-0184-y

Forrest, J. L., Wikramanayake, E., Shrestha, R., Areendran, G., Gyeltshen, K., Maheshwari, A., Mazumdar, S., Naidoo, R., Thapa, G. J., & Thapa, K. (2012). Conservation and climate change: Assessing the vulnerability of snow leopard habitat to treeline shift in the Himalaya. *Biological Conservation*, *150*(1), 129–135. https://doi.org/10.1016/j.biocon.2012.03.001

Forrester, J. W. (1994). System dynamics, systems thinking, and soft OR. *System Dynamics Review*, *10*(2).

Galvani, A. P., Bauch, C. T., Anand, M., Singer, B. H., & Levin, S. A. (2016). Human-environment interactions in population and ecosystem health. In *Proceedings of the National Academy of Sciences of the United States of America* (Vol. 113, Issue 51, pp. 14502–14506). National Academy of Sciences. https://doi.org/10.1073/pnas.1618138113

García, J. T., Jiménez, J., Mateo, R., & Arroyo, B. (2016). *Current Trends in Wildlife Research*. *1*, 283–293. https://doi.org/10.1007/978-3-319-27912-1

Garcia, R. A., Cabeza, M., Rahbek, C., & Araújo, M. B. (2014). Multiple dimensions of climate change and their implications for biodiversity. In *Science* (Vol. 344, Issue 6183). American Association for the Advancement of Science. https://doi.org/10.1126/science.1247579

Gedir, J. v, Cain, J. W., Swetnam, T. L., Krausman, P. R., & Morgart, J. R. (2020). Extreme drought and adaptive resource selection by a desert mammal. *Ecosphere*, *11*(17). https://doi.org/doi:e03175. 10.1002/ecs2.3175

González-Saldívar, F., Tarango-Arámbula, L. a, Cantú-Ayala, C., Uvalle-Sauceda, J., Marmolejo-Moncivais, J., & Ríos-Saldaña, C. (2012). Estudio Poblacional y de distribución del borrego cimarrón (Ovis canadensis mexicana , merriam , 1901) en Sonora. *Revista Mexicana de Ciencias Forestales*, *2*(4), 63–75.

Graziano, M. P., Deguire, A. K., & Surasinghe, T. D. (2022). Riparian Buffers as a Critical Landscape Feature: Insights for Riverscape Conservation and Policy Renovations. In *Diversity* (Vol. 14, Issue 3). MDPI. https://doi.org/10.3390/d14030172

Grinnell, J. (1917). The Niche-Relationships of the California Thrasher. *The Auk JSTOR*, *34*(4), 427–433.

Groves, D. G., Bonzanigo, L., Syme, J., Engle, N. L., & Rodriguez Cabanillas, I. (2019). *Preparing for Future Droughts in Lima, Peru: Enhancing Lima's Drought Management Plan to Meet Future Challenges. Washington, DC: World Bank*.

Groves, D. G., Kuhn, K., Fischbach, J. R., Johnson, D. R., & Syme, J. (2016). *Analysis to Support Louisiana's Flood Risk and Resilience Program and Application to the National Disaster Resilience Competition*.

Groves, D. G., & Lempert, R. J. (2007). A new analytic method for finding policy-relevant scenarios. *Global Environ. Change*, *17*, 73–85.

Guerrero-Cárdenas, I., Tovar-Zamora, I., & Álvarez-Cárdenas, S. (2003). Factores que afectan la distribución espacial del borrego cimarrón Ovis canadensis weemsi en la Sierra del Mechudo ,. *Anales Del Instituto de Biología, Universidad Nacional Autónoma de México, Serie Zoología*, *74*(195), 83–98.

Guerry, A. D., Polasky, S., Lubchenco, J., Chaplin-Kramer, R., Daily, G. C., Griffin, R., Ruckelshaus, M., Bateman, I. J., Duraiappah, A., Elmqvist, T., Feldman, M. W., Folke, C., Hoekstra, J., Kareiva, P. M., Keeler, B. L., Li, S., McKenzie, E., Ouyang, Z., Reyers, B., … Vira, B. (2015). Natural capital and ecosystem services informing decisions: From promise to practice. In *Proceedings of the National Academy of Sciences of the United States of America* (Vol. 112, Issue 24, pp. 7348–7355). National Academy of Sciences. https://doi.org/10.1073/pnas.1503751112

Guisan, A., Tingley, R., Baumgartner, J. B., Naujokaitis-Lewis, I., Sutcliffe, P. R., Tulloch, A. I. T., Regan, T. J., Brotons, L., Mcdonald-Madden, E., Mantyka-Pringle, C., Martin, T. G., Rhodes, J. R., Maggini, R., Setterfield, S. A., Elith, J., Schwartz, M. W., Wintle, B. A., Broennimann, O., Austin, M., … Buckley, Y. M. (2013). Predicting species distributions for conservation decisions. *Ecology Letters*, *16*(12), 1424–1435. https://doi.org/10.1111/ele.12189

Gunderson, L. H., & Holling, C. S. (2002). *Panarchy:Undestanding Transformations in Human and Natural Systems* (L. H. Gunderson & C. S. Holling, Eds.). Island Press.

Head, B. W., & Alford, J. (2015). Wicked Problems: Implications for Public Policy and Management. *Administration and Society*, *47*(6), 711–739. https://doi.org/10.1177/0095399713481601

Heffelfinger, J. R., & Marquez-Muñoz, E. (2005). Historical occurrence and distribution of desert bighorn sheep in Chihuahua , Mexico. *DESERT BIGHORN COUNCIL TRANSACTIONS*, *48*, 28–38.

Helena, C. (2020). *Translocación y reintroducción como estrategias complementarias para la conservación del endémico y críticamente amenazado Paujil de pico azul (Crax alberti)*.

Hilty, J., Worboys, G. L., Keeley, A., Woodley, S., Lausche, B., Locke, H., Carr, M., Pulsford, I., Pittock, J., White, J. W., Theobald, D. M., Levine, J., Reuling, M., Watson, J. E. M., Ament, R., & Tabor, G. M. (2020). *Guidelines for conserving connectivity through ecological networks and corridors Best Practice Protected Area Guidelines Series No. 30 Developing capacity for a protected planet*. www.iucn.org/pa_guidelines

Hirzel, A. H., Lay L., Helfer, V., Randin, C., & Guisan, A. (2006). Evaluating the ability of habitat suitability models to predict species presences.(2006): 142-152. *Ecological Modelling*, 142–152.

Hoegh-Guldberg, O., Kenned, E., Beyer, H., McClennen, C., & Possingham, H. (2018). Securing a Long-term Future for Coral Reefs. *Trends in Ecology & Evolution*, *33*(12), 936–944.

Holling, C. S. (2001). Understanding Complexity of Economic, Ecological, and Social Systems. *Ecosystems*, *4*, 390–405.

Huerta-García, A., Ramírez-Milanés, M. N., Valenzuela-Núñez, L. M., & Abad-Zavaleta, J. (2015). Aprovechamiento del borrego cimarrón (Ovis canadensis mexicana) en unidades de manejo del noreste de México. *Ecosistemas y Recursos Agropecuarios*, *2*(6), 339–347.

Hughes, T. P., Carpenter, S., Rockström, J., Scheffer, M., & Walker, B. (2013). Multiscale regime shifts and planetary boundaries. *Trends in Ecology and Evolution*, *28*(7), 389–395. https://doi.org/10.1016/j.tree.2013.05.019

Hull, V., Tuanmu, M.-N., & Liu, J. (2015). Ecology and Society: Synthesis of human-nature feedbacks. *Ecology and Society*, *20*(3), 17. http://www.ecologyandsociety.org/vol20/iss3/art17/

IPCC. (2021a). *IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou, Eds.). Cambridge University Press.

IPCC. (2021b). Technical Summary. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In *Climate Change 2021: The Physical Science Basis.*

Islam, M. M., Sallu, S., Hubacek, K., & Paavola, J. (2014a). Vulnerability of fishery-based livelihoods to the impacts of climate variability and change: Insights from coastal Bangladesh. *Regional Environmental Change*, *14*(1), 281–294. https://doi.org/10.1007/s10113-013-0487-6

Islam, M. M., Sallu, S., Hubacek, K., & Paavola, J. (2014b). Vulnerability of fishery-based livelihoods to the impacts of climate variability and change: Insights from coastal Bangladesh. *Regional Environmental Change*, *14*(1), 281–294. https://doi.org/10.1007/s10113-013-0487-6

Isley, S. C., Lempert, R. J., Popper, S. W., & Vardavas, R. (2015). The effect of near-term policy choices on long-term greenhouse gas transformation pathways. *Glob. Environ. Change*, *34*, 147–158.

Kalra, N., Hallegatte, S., Lempert, R., Brown, C., Fozzard, A., Gill, S., & Shah, A. (2014). *Agreeing on Robust Decisions New Processes for Decision Making Under Deep Uncertainty*. http://econ.worldbank.org.

Karger, D. N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R. W., Zimmermann, N. E., Linder, H. P., & Kessler, M. (2018). *Data from: Climatologies at high resolution for the earth's land surface areas*. https://doi.org/10.5061/dryad.kd1d4

Kasprzyk, J. R., Nataraj, S., Reed, P. M., & Lempert, R. J. (2013). Many objective robust decision making for complex environmental systems undergoing change. *Environ. Model. Softw.*, *42*, 55–71.

Kates. (2001). Sustainability Science. *Science*, *292*(5517), 641–642. https://doi.org/10.1126/science.1059386

Kengar, A., Vinayake, K., Mallia, J., Darade. M, Kumar, B., & Chahande, S. (2021). *Ecology Research* (A. Kengar, M. Darade, K. Vinayake, B. Kumar, J. Mallia, & S. Chahande, Eds.; Vol. 2).

Köberle, A. C., Vandyck, T., Guivarch, C., Macaluso, N., Bosetti, V., Gambhir, A., Tavoni, M., & Rogelj, J. (2021). The cost of mitigation revisited. In *Nature Climate Change*. Nature Research. https://doi.org/10.1038/s41558-021-01203-6

Kwakkel, J. H. (2017). The exploratory modeling workbench: an open source toolkit for exploratory modeling, scenario discovery, and (multiobjective) robust decision making. . *Environ. Model. Softw.* , *96*, 239–250.

Langridge, J., Sordello, R., & Reyjol, Y. (2020a). Outcomes of wildlife translocations in protected areas: what is the type and extent of existing evidence? A systematic map protocol. *Environmental Evidence*, *9*(1). https://doi.org/10.1186/s13750-020-00199-4

Langridge, J., Sordello, R., & Reyjol, Y. (2020b). Outcomes of wildlife translocations in protected areas: what is the type and extent of existing evidence? A systematic map protocol. *Environmental Evidence*, *9*(1). https://doi.org/10.1186/s13750-020-00199-4

Langridge, J., Sordello, R., & Reyjol, Y. (2021). Existing evidence on the outcomes of wildlife translocations in protected areas: a systematic map. *Environmental Evidence*, *10*(1). https://doi.org/10.1186/s13750-021-00236-w

Larson, A. M., & Ribot, J. C. (2007). The poverty of forestry policy: Double standards on an uneven playing field. *Sustainability Science*, *2*(2), 189–204. https://doi.org/10.1007/s11625-007-0030-0

Lee, R. (2003). A review of recent wild sheep surveys in Baja California Sur, Mexico. *Desert Bighorn Council Transaction*, *43*, 43–46.

Lee, R. (2008). Hunting as a Tool For Wildlife Conservation: The Case of Sheep Hunting in Mexico. In R. D. Baldus, G. R. Damm, & K. Wollscheid (Eds.), *Best Practices in Sustainable Hunting A Guide to Best Practices From Around the World*.

Lee, R. (2016). *Monitoreo Aéreo de la Población de Borrego Cimarron en Baja California Sur (2016). Reporte Técnico No Publicado*.

Lempert, R. (2015). Selection of climate policies under the uncertainties in the Fifth Assessment Report of the IPCC. *Nature Climate Change*, *5*(10), 937–943. https://doi.org/10.1038/nclimate2721

Lempert, R. J., & Groves, D. G. (2010). Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west. *Technol. Forecast. Soc. Change*, *77*, 960-974.

Lempert, R. J., Groves, D. G., Popper, S., & Bankes, S. C. (2006). A general, analytic method for generating robust strategies and narrative scenarios. *Manag. Sci.*, *52*, 514–528.

Lempert, R. J., Popper, S. W., & Bankes, S. C. (2003). *Shaping the next one hundred years : new methods for quantitative, long-term policy analysis and bibliography*. RAND.

Levin, S. (1998). The Ecosystems and Biosphere Complex Adaptive Systems. *Ecosystems*, 431–436.

Levin, S., Xepapadeas, T., Crépin, A.-S., Norberg, J., de Zeeuw, A., Folke, C., Hughes, T., Arrow, K., Barrett, S., Daily, G., Ehrlich, P., Kautsky, N., Mäler, K.-G., Polasky, S., Troell, M., Vincent, J. R., & Walker, B. (2013). Social-ecological systems as complex adaptive systems: modeling and policy implications. *Environment and Development Economics*, *18*(02), 111–132. https://doi.org/10.1017/S1355770X12000460

Lindig, R., Galindo, S., & Lara, S. (2006). Historical distribution of desert bighorn sheep (ovis canadensis mexicana) in Coahuila Mexico. *The Southwestern Naturalist*, *51*(4), 455–461. https://doi.org/10.1894/0038-4909(2006)51

Liu, J., Hull, V., Batistella, M., DeFries, R., Dietz, T., Fu, F., Hertel, T. W., Izaurralde, R. C., Lambin, E. F., Li, S., Martinelli, L. A., McConnell, W. J., Moran, E. F., Naylor, R., Ouyang, Z., Polenske, K. R., Reenberg, A., Rocha, G. de M., Simmons, C. S., … Zhu, C. (2013). Framing Sustainability in Telecoupled World. *Ecology and Society 18(2):*, *18*(12), 26. https://doi.org/. http://dx.doi.org/10.5751/ ES-05873-180226 Synthesis

López-Feldman, A., & Wilen, J. E. (2008). Poverty and spatial dimensions of non-timber forest extraction. *Environment and Development Economics*, *13*(05), 1–43. https://doi.org/10.1017/S1355770X08004518

Lynam, T., de Jong, W., Sheil, D., Kusumanto, T., & Evans, K. (2007). A review of tools for incorporating community knowledge, preferences, and values into decision making in natural resources management. *Ecology and Society* , *12*(1).

Maida, C. A., & Beck, S. (2018). *Global Sustainability and Communities of Practice* (1st ed.). Berghahn Books JSTOR.

Manterola, C. (2001). *Censo aéreo de poblaciones de borrego cimarrón (Ovis canadensis cremnobates) en Baja California , México*.

Manterola y Piña, C. (1999). Monitoreo de las poblaciones de borrego cimarrón (Ovis canadensis weemsi) en Baja California Sur, México. In *SNIB-CONABIO*.

Marchau, V. A. W. J., Walker, W. E., Bloemen, M., P. J. T., & Popper, S. W. (2019). Decision Making Under Deep Uncertainty. In V. A. W. J. Marchau, W. E. Walker, P. J. T. Bloemen, M., & S. W. Popper (Eds.), *The Oxford Handbook of Planning for Climate Change Hazards*. https://doi.org/10.1093/oxfordhb/9780190455811.013.50

Marchau, V., Walker, W. E., A.Bloemen, P. J., & Popper, S. W. (2019). *Decision Making under Deep Uncertainty*. Springer International Publishing. https://doi.org/10.1007/978-3-030-05252-2

Mayer, I. S., van Daalen, C. E., & Bots, P. W. G. (2004). Perspectives on policy analyses: A framework for understanding and design. In *International Journal of Technology, Policy and Management* (Vol. 4, Issue 2, pp. 169–191). Inderscience Publishers. https://doi.org/10.1504/IJTPM.2004.004819

Mckinney, T., Smith, T., & DeVos, J. (2003). Evaluation of Factors Potentially Influencing a Desert Bighorn Sheep Population. *The Wildlife Society*, *0173*, 1–36.

Medeiros, E. (2016). Is there a rise of the territorial dimension in the EU Cohesion Policy ? *Finisterra*.

Meltzer, R., & Schwartz, A. (2019). *Policy Analysis as Problem Solving: A Flexible and Evidence-Based Framework*. Routledge.

Mesa, E. (2013). *Diagnóstico del hábitat del borrego cimarrón en funcion de variables ambientales y actividades antropogénicas en la sierra El Mechudo Baja California Sur, México.* Centro de Investigaciones Biológicas del Noreste, S. C.

Milner-Gulland, E. J. (2012). Interactions between human behaviour and ecological systems. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*(1586), 270–278. https://doi.org/10.1098/rstb.2011.0175

Molina-Perez, E., Esquivel-Flores, O. A., & Zamora-Maldonado, H. (2020). Computational Intelligence for Studying Sustainability Challenges: Tools and Methods for Dealing With Deep Uncertainty and Complexity. *Frontiers in Robotics and AI*, *7*. https://doi.org/10.3389/frobt.2020.00111

Molina-Perez, E., Groves, D. G., Popper, S. W., Ramirez, A. I., & Crespo-Elizondo, R. (2019). *Developing a robust water strategy for Monterrey, Mexico : diversification and adaptation for coping with climate, economic, and technological uncertainties*.

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H., & Schwarz, N. (2013). Describing human decisions in agent-based models - ODD+D, an extension of the ODD protocol. *Environmental Modelling and Software*, *48*, 37–48. https://doi.org/10.1016/j.envsoft.2013.06.003

Murray, C., & Marmorek, D. (2003). Adaptive Management and Ecological Restoration. In P. Freiderici (Ed.), *Ecological Restoration of Southwestern Ponderosa Pine Forests* (pp. 417–428). Island Press.

Nelson, D. R., Adger, W. N., & Brown, K. (2007). Adaptation to Environmental Change: Contributions of a Resilience Framework. *Annual Review of Environment and Resources*, *32*(1), 395–419. https://doi.org/10.1146/annurev.energy.32.051807.090348

O´Farril, E. (2003). *Dieta y uso del hábitat del borrego cimarrón (Ovis canadensis mexicana) y el venado bura (Odocoileus hemionus sheldoni) en Isla Tiburón, Sonora, México*. Universidad Nacional Autónoma de México.

O'Higgins, T. G., Lago, M., & DeWitt, T. H. (2020). *Ecosystem-Based Management, Ecosystem Services and Aquatic Biodiversity* (T. G. O'Higgins, M. Lago, & T. H. DeWitt, Eds.). Springer. https://doi.org/https://doi.org/10.1007/978-3-030-45843-0

Oliver, K., & Cairney, P. (2019). The dos and don'ts of influencing policy: a systematic review of advice to academics. In *Palgrave Communications* (Vol. 5, Issue 1). Palgrave Macmillan Ltd. https://doi.org/10.1057/s41599-019-0232-y

Ordoñez-Matamoros. (2013). *Manual de Análisis y Diseño de Políticas Públicas*. Panamericana.

Ostrom, E. (2005). *Understanding Institutional Diversity*. Princeton University Press.

Ostrom, E. (2009). A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science*, *325*, 419–423.

Owen, G. (2020). What makes climate change adaptation effective? A systematic review of the literature. *Global Environmental Change*, *62*. https://doi.org/10.1016/j.gloenvcha.2020.102071

Palomo-Ramos, R., Ramos, P., Colima, G., & Arana, R. (n.d.). *REVISTA BIO CIENCIAS Translocation as a conservation tool for endangered tortoises in Mexico Las translocaciones como herramienta de conservación para las tortugas terrestres en México*. https://doi.org/10.15741/revbio.05.01.01

Parker, J., Simpson, G. D., & Miller, J. E. (2020). Nature-based solutions forming urban intervention approaches to anthropogenic climate change: A quantitative literature review. In *Sustainability (Switzerland)* (Vol. 12, Issue 18). MDPI. https://doi.org/10.3390/SU12187439

Pereira, H., Leadleyvania, P., & Proença, V. (2010). Scenarios for Global Biodiversity in the 21st Century. *Science*, *330*(6010).

Perry, D. C., Chaffee, C., Wigand, C., & Thornber, C. (2020). Implementing adaptive management into a climate change adaptation strategy for a drowning New England salt marsh. *Journal of Environmental Management*, *270*. https://doi.org/10.1016/j.jenvman.2020.110928

Peterson, T., & Anamza, T. (2015). Ecological niches and present and historical geographic distributions of species: a 15-year review of frameworks, results, pitfalls, and promises. *Folia Zoologica*, *64*(3), 207–217.

Phillips, S. J., Anderson, R. P., Dudík, M., Schapire, R. E., & Blair, M. E. (2017). Opening the black box: an open-source release of Maxent. *Ecography*, *40*(7), 887–893. https://doi.org/10.1111/ecog.03049

Phillips, S. J., & Dudík, M. (2008). *Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation*. https://doi.org/10.1111/j.2007.0906-7590.05203.x

Pires, A. P. F., Srivastava, D. S., Marino, N. A. C., Andrew, A., Macdonald, M., Figueiredo-Barros, M. P., & Farjalla, V. F. (2018). *Interactive effects of climate change and biodiversity loss on ecosystem functioning*.

Popper, S. W., Berrebi, C., Griffin, J., Crane, K., Light, T., & Daehner, E. M. (2009). *Natural Gas and Israel's Energy Future*.

Ramirez-Villegas, J., Devenish, F., & Cuesta, F. (2014). Using species distributions models for designing conservation strategies of Tropical Andean biodiversity under climate change. *Nature Conservation*, *22*(5), 391–404.

Ramos, P., Colima, G., & Arana, R. (2018). Translocation as a conservation tool for endangered tortoises in Mexico. *REVISTA BIO CIENCIAS* . https://doi.org/10.15741/revbio.05.01.01

Resilience Alliance. (2015). ASSESSING RESILIENCE IN SOCIAL-ECOLOGICAL SYSTEMS. *Stockholm University*, *June*, 1–53. http://www.stockholmresilience.org/21/research/what-is-resilience/research-background/research-framework/social-ecological-systems.html

Robinson, J. G., & Bennett, E. (2001). *Hunting for Sustainability in Tropical Forests* (J. G. Robinson & E. Bennett, Eds.; Vol. 39). Columbia University Press,.

Rodríguez-Ríos, E., & García-Páez, B. (2017). Valuing bushmeat for people living at a subsistence level: The case of *Cuniculus paca* meat in Flavio Alfaro, Manabí, Ecuador. *Human Dimensions of Wildlife*. https://doi.org/10.1080/10871209.2018.1419517

Román, R. (2012). *Densidad y estructura poblacional del Borrego Cimarrón (Ovis canadensis weemsi, Goldman, 1937) en la Isla "El Carmen", Baja California Sur, México*. Universidad Autónoma de Nuevo León.

Ruíz, E. (2014). *Estado actual de la población de borrego cimarrón (Ovis canadensis weemsi) En la UMA ejido La Purísima, Baja California Sur, México*. Universidad Nacional Autónoma de México.

Saavedra, E., Lee, R. M., de Vos, J. C., Schweinsburg, R. E., & Salazar, G. (1999). Relación Uso-Disponibilidad De Componentes Topográficos Y Un Modelo De Calidad Del Hábitat Para El Borrego Cimarrón, En Sonora, México. *Acta Zoológica Mexicana (Ns)*, *76*, 17–34.

Saba, V. S., Stock, C. A., Spotila, J. R., Paladino, F. v., & Tomillo, P. S. (2012a). Projected response of an endangered marine turtle population to climate change. *Nature Climate Change*, *2*(11), 814–820. https://doi.org/10.1038/nclimate1582

Saba, V. S., Stock, C. A., Spotila, J. R., Paladino, F. v., & Tomillo, P. S. (2012b). Projected response of an endangered marine turtle population to climate change. *Nature Climate Change*, *2*(11), 814–820. https://doi.org/10.1038/nclimate1582

SAGARHPA. (2012). Borrego cimarrón (Ovis canadensis mexicana): Resultados del monitoreo aéreo en el Estado de Sonora, México. Noviembre, 2012. In *SAGARHPA*. http://www.hunting.sonora.gob.mx/convenios/libro.pdf

Scarlett, L. (2013). Collaborative adaptive management: Challenges and opportunities. *Ecology and Society*, *18*(3). https://doi.org/10.5751/ES-05762-180326

Scheffer, M., & Carpenter, S. R. (2003). Catastrophic regime shifts in ecosystems: Linking theory to observation. *Trends in Ecology and Evolution*, *18*(12), 648–656. https://doi.org/10.1016/j.tree.2003.09.002

Schlüter, M., Müller, B., & Frank, K. (2019). The potential of models and modeling for social-ecological systems research: The reference frame ModSES. *Ecology and Society*, *24*(1). https://doi.org/10.5751/ES-10716-240131

Schlüter, M., Orach, K., Lindkvist, E., Martin, R., Wijermans, N., Bodin, Ö., & Boonstra, W. J. (2019). Toward a methodology for explaining and theorizing about social-ecological phenomena. *Current Opinion in Environmental Sustainability*, *39*, 44–53. https://doi.org/10.1016/j.cosust.2019.06.011

Schoenecker, K. A. (2004). Bighorn Sheep Habitat Studies , Population Dynamics , and Population Modeling in Bighorn Canyon National Recreation Area , 2000 – 2003. *Recreation*, 216.

Schwartz, M. (2012). Using niche models with climate projections to inform conservation management decisions. *Biological Conservation*, *155*, 149–156.

SEMARNAT. (2012). Estrategia Estatal Para la Conservación y Manejo Sustentable del Borrego Cimarrón (Ovis canadensis cremnobates) en Baja California. *SEMARNAT*, 91.

Seppelt, R., Müller, F., Schröder, B., & Volk, M. (2009). Challenges of simulating complex environmental systems at the landscape scale: a controversial dialogue between two cups of espresso . *Ecological Modeling*, *220*, 3481–3489.

Spencer, R., & Janzen, F. (2010). Demographic consequences of adaptive growth and the ramifications for conservation of long-lived organisms. *Biological Conservation*, *143*(9), 1951–1959.

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

Sumaila, U. R., Cheung, W. W. L., Lam, V. W. Y., Pauly, D., & Herrick, S. (2011a). Climate change impacts on the biophysics and economics of world fisheries. In *Nature Climate Change* (Vol. 1, Issue 9, pp. 449–456). https://doi.org/10.1038/nclimate1301

Sumaila, U. R., Cheung, W. W. L., Lam, V. W. Y., Pauly, D., & Herrick, S. (2011b). Climate change impacts on the biophysics and economics of world fisheries. In *Nature Climate Change* (Vol. 1, Issue 9, pp. 449–456). https://doi.org/10.1038/nclimate1301

Tarango, L. a., Krausman, P. R., Valdez, R., & Kattnig, R. M. (2006). Research observation: desert bighorn sheep diets in northwestern Sonora, Mexico. *Journal of Range Management Archives*, *55*(6), 530–534. https://doi.org/10.2307/4003995

Tingstad, A. H., Lempert, R. J., Moskwik, M., Warren, D. L., Parmesan, C., Mcginnis, S., & Ryu, Y. (2017). Demonstrating the Applicability of a Robust Decision Making (RDM) to Conservation Decision-Making Under Uncertain Future Climate: Pilot Study Using the Northern Pygmy Salamander (Desmognathus organi). In *Journal of Conservation Planning* (Vol. 13).

Turner, J. C., & Weaver, A. (1980). Water. In G. Monson & L. Sumner (Eds.), *The desert bighorn: Its life history, ecology and management* (p. 370). Univ. Arizona Press.

Valdés-Alarcón, M., & Segundo-Galán, M. (2011). Estrategias de conservación en México para el borrego cimarrón (Ovis canadensis) y el berrendo (Antilocapra americana). In O. Sánchez, P. Zamorano, E. Peters, & H. Moya (Eds.), *Temas sobre Conservación de Vertebrados en México* (pp. 277–309). INECC-SEMARNAT. http://www2.inecc.gob.mx/publicaciones/libros/646/estrategias.pdf

van Mierlo, B., & Beers, P. J. (2020). Understanding and governing learning in sustainability transitions: A review. *Environmental Innovation and Societal Transitions*, *34*, 255–269. https://doi.org/10.1016/j.eist.2018.08.002

Velazquez, A., & Heil, G. W. (1996). "Habitat suitability study for the conservation of the volcano rabbit (Romerolagus diazi). *Journal of Applied Ecology*, 543–554.

Villarreal, G. (2012). *Introducción al manejo y aprovechamiento sustentable de la fauna silvestre en ranchos ganaderos diversificados*.

Walker, B., Gunderson, L., Kinzig, A., Folke, C., Carpenter, S., & Schultz, L. (2006). A handful of heuristics and some propositions for understanding resilience in social-ecological systems. *Ecology and Society*, *11*(1). https://doi.org/[online] URL:http://www.ecologyandsociety.org/vol11/iss1/art13/

Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, Adaptability and Transformability in Social – ecological Systems. *Ecology and Society*, *9*(2), 5. https://doi.org/10.1103/PhysRevLett.95.258101

Walker, B., & Salt, D. (2006). *Resilience Thinking: Sustaining Ecosystems and People in a Changing World*. Island Press.

Walker, B., & Salt, D. (2012). *Resilience Practice. Building Capacity to Absorb Disturbance and Mantain Function*. Islandpress.

Wang, T., Campbell, E. M., O'Neill, G. A., & Aitken, S. N. (2012). Projecting future distributions of ecosystem climate niches: Uncertainties and management applications. *Forest Ecology and Management*, *279*, 128–140. https://doi.org/10.1016/j.foreco.2012.05.034

Westley, F., Olsson, P., Folke, C., Homer-Dixon, T., Vredenburg, H., Loorbach, D., Thompson, J., Nilsson, M., Lambin, E., Sendzimir, J., Banerjee, B., Galaz, V., & van der Leeuw, S. (2011). Tipping toward sustainability: Emerging pathways of transformation. *Ambio*, *40*(7), 762–780. https://doi.org/10.1007/s13280-011-0186-9

Weyant, J., Davidson, O., Dowlatabadi, H., Edmonds, J., Grubb, M., Parson, E. A., Richels, R., Rotmans, J., Shukla, P., Tol, R. S. J., Cline, W., & Fankhauser, S. (1996). Integrated assessment of climate change: An overview and comparison of approaches and results. In J. P. Bruce, H. L. Haites, & E. F. Haites (Eds.), *Economic and Social Dimensions of Climate Change* (pp. 371–393). IPCC, Cambridge University Press.

Whiting, J., Bleich, R., Vernon, T., Bowyer, T., & Larsen, R. (2012). WATER AVAILABILITY AND BIGHORN SHEEP: LIFE-HISTORY CHARACTERISTICS AND PERSISTENCE OF POPULATIONS. In J. A. Daniels (Ed.), *Advances in Environmental Research.* Nova Science Publishers, Inc.

Wiek, A., Withycombe, L., & Redman, C. L. (2011). Key competencies in sustainability: A reference framework for academic program development. *Sustainability Science*, *6*(2), 203–218. https://doi.org/10.1007/s11625-011-0132-6

Wilder, B. T., Betancourt, J. L., Epps, C. W., Crowhurst, R. S., Mead, J. I., & Ezcurra, E. (2014). Local extinction and unintentional rewilding of bighorn sheep (Ovis canadensis) on a Desert Island. *PLoS ONE*, *9*(3). https://doi.org/10.1371/journal.pone.0091358

Williams, B. K., & Brown, E. D. (2014). Adaptive management: From more talk to real action. *Environmental Management*, *53*(2), 465–479. https://doi.org/10.1007/s00267-013-0205-7

Williams, B. K., & Brown, E. D. (2016). Technical challenges in the application of adaptive management. *Biological Conservation*, *195*, 255–263. https://doi.org/10.1016/j.biocon.2016.01.012

Zhong, L., Ma, Y., & Salama, M. S. (2010). Assessment of vegetation dynamics and their response to variations in precipitation and temperature in the Tibetan Plateau. *Climatic Change*, *103*, 519–535.

III. CAPÍTULO 2

Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico

Abstract

Bighorn sheep (*Ovis canadensis*) management systems are a social-ecological system (SES) in which different pathways can determine the system's resilience in response to climate stressors. Thus, the aim of this study is to build a dynamic model to assess whether the system is resilient to water stress. In this study, the SES is considered resilient if the bighorn population is sufficiently large to provide economic revenues to landowners and promote conservation action. We validate and formalize this model by conducting semi-structured interviews with Ejido Bonfil landowners located in Baja California Sur and experts in the field of recreational hunting and wildlife management. To explore the changes in SES resilience, we conduct simulations to assess the impact of rainfall variability patterns on the system. Our results indicate that rainfall variations with respect to the historical record have the potential to disrupt both the species and the local economy and that the lack of an adaptive capacity in a harvest strategy may affect the dynamics of the whole SES. Finally, this paper explores how adaptive wildlife management strategies can enhance the resilience of both subsystems in this SES.

Keywords
Social-ecological systems, bighorn sheep, resilience, climate change, dynamic modeling

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

1. Introduction

Wildlife management requires an understanding of the complex interactions between socioeconomic and ecological systems (Schlüter et al. 2011) to identify systemic changes and in turn guide sustainable practices. Wildlife management is a social-ecological system (SES) implemented to conserve wildlife species and social benefits. Its structure is composed of social and biological subsystems, and the feedbacks across them determine the conjoint optimization of both subsystems to sustain the thresholds and overall functionality in terms of sustainability. All SESs are exposed to shocks and stressors, such as climatic changes and extreme events. Climate change adds challenges for wildlife management due to uncertain changes in species ranges and ecological dynamics.

A SES model must be conceptualized in terms of their components and interactions, which is formalized by identifying specific variables and mathematical functions and finally operationalized by testing system dynamics and resilience with empirical data. Schlüter et al. (2014) and Polhill et al. (2015) pointed out the methodological challenges associated with the use of modeling and simulation to study SES behavior. However, SES modeling serves as a tool for assessing management strategies by developing a simplified representation of the SES structure, mechanisms and processes. Moreover, empirical analyses of SESs are difficult due to the nonlinear interactions among variables, SES responses at different scales and lack of field data for describing relevant variables.

Particularly, modelling wildlife recreation hunting is important since it is a controversial activity (Leader-Williams 2009), and the model allows for an exploration of this activity's potential to increase the welfare of local stakeholders and simultaneously sustain and preserve wildlife (Adams et al. 2009). Communities and ecosystems where recreational

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

hunting occurs are very diverse; consequently, this activity produces a diversity of outcomes that are not always positive for biodiversity and livelihoods at the same time (Jones 2009). As a result, determining the socioeconomic and ecological implications of this activity without the aid of integrative and exploratory tools is difficult. We address the feasibility of this activity from a systemic perspective that considers local social-ecological complexity and the environmental uncertainty under which this activity is carried out, which in turn provides elements to assess the resilience of the system.

This research implements the modelling approach as a tool for understanding and assessing complex systems, such as SESs (Gotts et al. 2018) (Bueno 2012, Filatova et al. 2015, Polhill et al. 2015). This approach is considered valuable in assisting reasoning about SES behavior (Bueno 2012, Filatova et al. 2015, Polhill et al. 2015) because it facilitates the identification of SES changes and transformations and characterization of its resilience (Carpenter and Gunderson 2001, Schlüter and Pahl-Wostl 2007, Schlüter et al. 2009, Lade et al. 2013, Brown and Williams 2015). Resilience means that a system is able to maintain its overall functions, structure, identity and feedbacks despite unexpected shocks, disturbances and reorganization (Walker et al. 2004). Moreover, resilience associated with sustainability emphasizes the need to manage change through adaptation and transformation (Levin et al. 1998, Holling 2001, Berkes et al. 2003, Folke et al. 2010, Folke 2016).

The SES resilience approach has been the focus of researchers who have developed dynamic analytical models. While these models perform well at analyzing the local decisions of multiple agents in the management of a resource system (Schlüter et al. 2009, Lade et al. 2013, Brown and Williams 2015), the implications of structural organizations

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

for the functioning of the system (Schlüter and Pahl-Wostl 2007) and the economic costs when the system crosses the biophysical threshold (Carpenter et al., 2001), they do not consider the potential adaptive responses to changing ecological dynamics that may affect the socioeconomic subsystem. In addition, none of these approaches focuses on wildlife management.

Most wildlife management strategies only consider the population size and the harvest rate for wildlife conservation; however, a resilient and systemic perspective can be illustrative of the need to consider more multidimensional approaches that explicitly link rainfall scarcity as a consequence of climate change in the region with both economic and environment systems, which is particularly relevant for wildlife managers as they work at a complex interface of biological, socioeconomic and climatic forces that determine the systems' functions, identity, structure and feedbacks. Hence, management actions implemented to address climate change influence regime shifts and the reorganization of the SES itself.

This paper aims to advance resilience modeling of SESs by integrating empirical data that encompass biological and socioeconomic feedbacks. This paper shows how the SES model can be operationalized to explore the SES resilience to climate stress (e.g., water stress). In this regard, Schlüter et al. (2014) recognized that this step is not a trivial one. To meet this challenge, we assessed resilience by considering the ability of the SES to maintain its structure and functions and thus sustain recreational hunting activity. We apply this approach to tourism associated with hunting bighorn sheep in Baja California Sur, Mexico. This economic activity has the potential to promote win-win solutions for conservation and development (Leão et al. 2017). Managing wildlife populations and habitats allows for

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

greater resource availability, which supports social benefits and in turn conservation, thereby creating feedbacks between society and conservation.

Moreover, this paper explores the importance of adaptive conservation strategies by conducting a series of experiments using computational tools to analyze complex and uncertain systems. Our contribution to the wildlife management arena is the exploratory analysis as a first attempt to analyze SES resilience to a specific stressor by anticipating actions and potential associated adaptive measures that consider the species conservation and revenues that promote habitat conservation. This dynamic model enhances our systemic understanding of non-lineal interactions and invites a discussion among stakeholders about how different management strategies could address the effects of the stressor by identifying the SES's thresholds and implementing precautionary management measures associated with the recreational hunting of bighorn sheep in a Management Unit for the Conservation of Wildlife (UMA). This approach can be used with other species and socioeconomic data to plan future strategies in the wildlife management arena that allow for long-term SES resilience oriented towards the sustainable management of natural resources. This means the development of best practices in fostering community wildlife management to reduce unsustainable and illegal use and trade of wildlife (Cooney et al., 2018).

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

1.1. Bighorn Sheep Management System

2.1 Management Unit for the Conservation of Wildlife (UMA)

Due to its vast grasslands and bushes, the northeastern region of Mexico is suitable for livestock diversification (Villarreal 2012). Recreational hunting is part of this diversified livestock strategy for ejido land ownerships. The UMA was originally created as a voluntary instrument with which to manage wildlife use as part of livelihood diversification, but it became obligatory in 1997 for any landowner wanting to use wildlife from its habitat. The number of UMAs registered by 2013 was 12,000, and these units have been increasing at a rate of 5% per year (DGVS, 2014), with a large majority and the most extensive ones located in the northern part of Mexico. This scheme has a larger extension than natural protected areas (Avila-Foucat and Pérez-Campuzano 2015). The policy aims to generate income for managers in the community and private lands derived from the conservation of species and their habitat. UMAs are operated under a management plan approved by the Secretariat of Environment and Natural Resources (SEMARNAT) for monitoring species and their habitats as well as for determining harvest rates. Income generation in UMAs is generated by both extractive (e.g., recreational hunting of individuals for ornaments or pets) and non-extractive uses (such as ecotourism), and wildlife management can be carried out in captivity or in the natural habitat, which are referred to as intensive and extensive management, respectively. In this case of recreational hunting, the majority of UMAs are extensive since animals are in the wild and extractive since the animals are hunted.

The Official Mexican Standard (NOM) 059-ECOL-1994 considers bighorn sheep (*Ovis canadensis weemsi*) as subject to special protection, and the Convention on International

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

Trade in Endangered Species of Wild Fauna and Flora (CITES) includes the species in Appendix II. In northwestern Mexico, bighorn sheep are distributed in the steep hills of the states of Sonora, Baja California, BCS, Chihuahua, Coahuila, and Nuevo Leon. The presence of three subspecies of bighorn sheep is recognized: *Ovis canadensis mexicana* (Merriam, 1901), *Ovis canadensis cremnobates* (Elliot, 1904) and *O. c. weemsi*. The subspecies *O. c. weemsi* is distributed mainly in the southern region of Baja California. Currently, extractive management is permitted in Sonora, BCS, Chihuahua, Coahuila, and Nuevo Leon but is prohibited in Baja California. Research on bighorn sheep habitat has revealed at least six key habitat criteria with which to determine areas of suitable habitat (Smith et al. 1991, Johnson and Swift 2000): horizontal visibility, proximity to perennial water sources, a minimum of natural and man-made barriers, human areas, proximity to exotic relatives and patch size. These criteria are also considered in the bighorn sheep management and conservation plan of the UMA Alfredo Vladimir Bonfil (UMA Bonfil). The Ministry of Environment oversees establishing the number of permits each year based on aerial surveys and estimation of the corresponding area and number of animals for each UMA.

1.2. UMA Alfredo Vladimir Bonfil

The UMA Bonfil in the state of BCS is dedicated to bighorn sheep recreational hunting, which generates important economic revenues (approximately US $757 per household in 2017). This activity allows for the recovery of this species since investments are performed for habitat conservation, which includes vigilance to keep poachers and feral cattle out of the bighorn sheep territory and watering maintenance (Carabias et al. 2010).

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

Similar to many other regions, Baja California suffers from rainfall absence periods or water stress, which could cause bighorn sheep populations to move. For instance, the Baja California action plan for climate change shows a temperature increase of 2 °C and an evapotranspiration rate of 80% compared to a recharge and runoff rate of 11% (Ivanova and Gámez 2012); according to national estimations Baja California is considered to have high drought vulnerability since 2013 (CONAGUA 2018). Under prolonged rainfall absence, the species could move north where the weather is cooler, which would lead to a decrease in the number of individuals in the region and the UMA. Although the implications of external stressors, such as climate change, have been analyzed in bighorn sheep populations (Epps et al. 2004, Colchero et al. 2009, Hauptfeld and Kershner 2014), research using a systemic perspective, including managers' and stakeholders' decisions with respect to adapting the current harvest strategy without compromising the economic stability of landowners, is lacking.

The UMA Bonfil was created in 1997 and has an extension of 519,000 hectares. The UMA generates 20 permanent employments and 30 temporary ones, mainly during December-March, which is the hunting season. The profits from the hunting activity are shared equally among the "ejidatarios", who are members of the UMA. In the UMA Bonfil, all 128 family heads and their members have the right to participate. The revenues gained by each landowner are discussed in an assembly after deciding the amount used for management of the UMA. Once this investment is set aside, the remaining funds are equally distributed.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

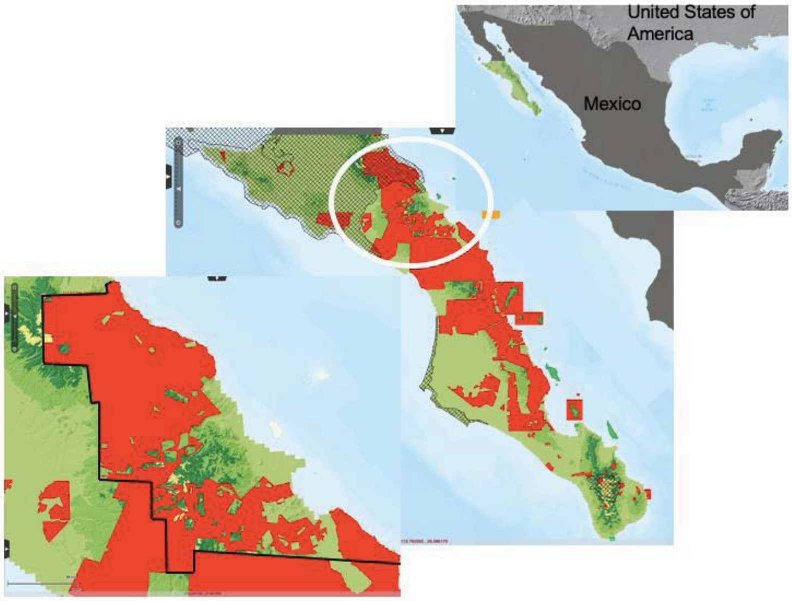


Figure 1. Study area (5,500 km²). Polygon in black line=E.A.V.B. (Ejido Alfredo Vladimir Bonfil, Baja California Sur, Mexico). Polygons in red=Wildlife Management Units (UMAs) in the state. Black grid area=Natural Protected Areas. Eighty percent of the ejido is part of the Natural Protected Area. Source: SEMARNAT http://gisviewer.semarnat.gob.mx/geointegrador/

1.3. Bighorn sheep hunting market

The bighorn sheep hunting market exists due to the demand for recreational hunting opportunities and international recreational hunting competitions. An example is the Grand Slam recognition, i.e., when a hunter harvests a ram of each of the 4 main subspecies (*Ovis dalli dalli, Ovis dalli stonei, Ovis canadensis canadensis*, and *Ovis canadensis nelsoni*) found in North America.

North American permits are auctioned in Reno, Nevada, U.S.A. The event is organized by the Foundation for North American Wild Sheep (FNAWS). Revenues from 1% of the auctioned permits are allocated to the FNAWS, the world's primary wild sheep conservation organization supporting wildlife management programs in 17 states in the U.S.A., 5 states in Mexico and 4 provinces in Canada. The revenue from the auction of permits is put into a "fideicomiso", a bank trust created between the Ejido and the FNAWS.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

Members of the UMA Bonfil participate in the annual convention by giving information on the advantages of hunting these specimens in the UMA territory (free-living specimens, the challenges of tracking, and the social benefits for the UMA). The initial price of the auction depends on several factors: the special protection status of the species in Mexican territory, management actions and characteristics in the UMA, the price of other hunting permits in Mexico and the purchasing power of the participants.

Hunters carry out recreational hunting as a tradition and, in some cases, belong to families with a hunting tradition. These people have very high incomes since they pay up to USD$70,000 for a hunting permit and up to USD $3,000 as a tip. Sometimes the hunters pay these amounts for up to 3 consecutive years. For a hunter of this type, hunting is the whole process of tracking, searching for, observing, and attempting to "collect" the prize (an animal's horns). Such hunters usually have up to 10 days for the entire process, and if they fail to hunt the prize in that time span, then they leave the UMA. Some hunters report that hunting is rewarding because it summarizes the overall effort; however, if they do not manage to kill the animal, then they interpret this as another opportunity for the animal to continue living. UMA members have even heard hunters say, "The Mountain claimed it". In summary, hunting is a competition between the hu.nter's skills and nature.

2. Model Construction Method

The construction of the recreational hunting SES dynamic model described in this paper consists of five stages (Fig. 1). The first stage is the conceptualization of the system in terms of the variables and interactions, mainly based on a literature review, and it represents the hypothesis of the system. The second stage is the formalization of the system, which includes determining and specifying the indicators or mathematical

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

relationships based on interviews to expand and validate the SES. The third stage includes the operationalization of the system, which involves measuring the changes in the system. The fourth stage includes implementing the system by using a computational model in R (R Core Team 2014), which is a language and environment for statistical computing. The final stage includes testing the effects of stressor trends and the design of experiments. The experimentation also proposes management adaptation strategies for each of the trends that combine 1) changes in the current harvest rate rule and 2) the introduction of new bighorn sheep individuals to sustain the bighorn sheep population in the UMA.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

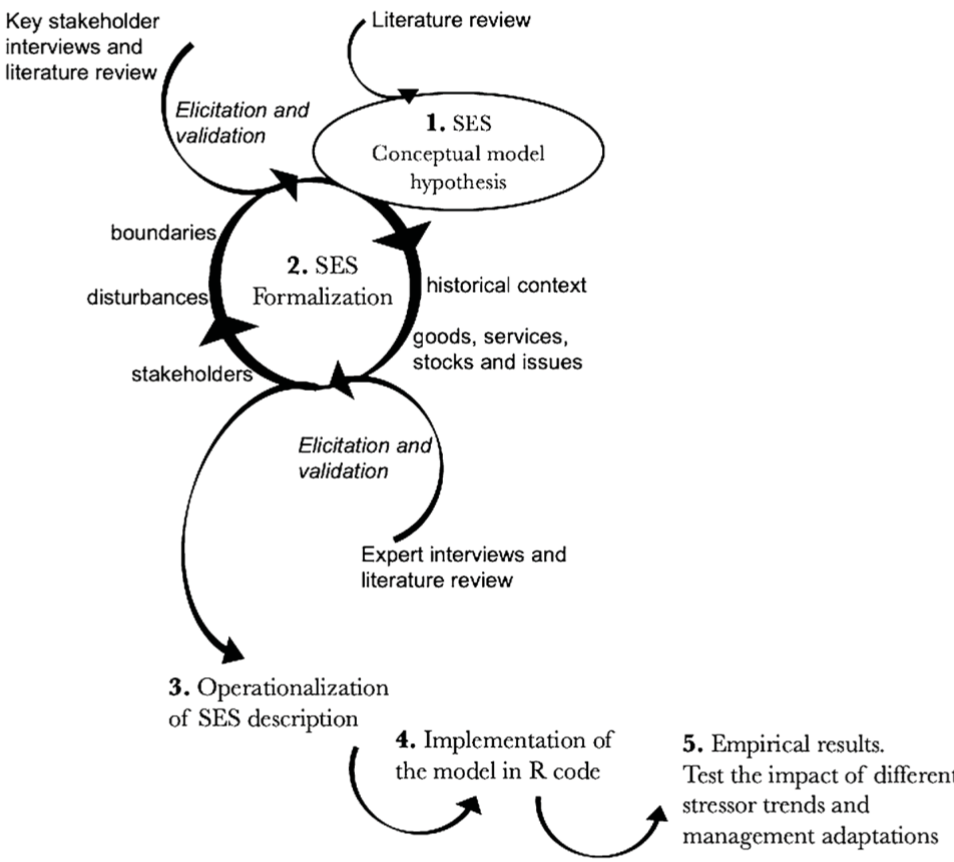


Figure *2.* Stages in the construction of the SES exploratory model. This diagram explains the overall process of model construction.

The conceptual model uses the five steps of Walker and Salt (2012): 1) identifying the system boundaries in time and space; 2) identifying groups of stakeholders or natural resource users; 3) identifying the stock that supports the recreational hunting SES and mapping the interactions between them in a conceptual model; 4) identifying the disturbances that stakeholders know and expect, which allows the resilience to be assessed with respect to specific dimensions; and 5) formulating a hypothesis of the system dynamics.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

Formalization of the SES followed a system dynamics approach where causal relationships are described by using a diagraming tool for mapping causal influences in a dynamic system (Forrester 1961). Positive causal influences are represented by a positive arrow from one variable to another.

Our SES consists of more than two causal relationships between elements that are called feedback loops. These elements are connected such that if we follow the causality starting at any element in the loop, we can eventually return to the first element. The conceptual model helps develop a dynamic hypothesis of how recreational hunting in this SES works. Based on these relationships, differential equations are developed for state variables; each equation is described in the results section. The operationalized model was written and run by using R code for clarity and transparency.

2.1.Data collection and elicitation process

Semi-structured interviews were conducted with experts and employees of the UMA Bonfil and the Mexican Commission of Natural Protected Areas (CONANP). Key stakeholders for the UMA Bonfil are the chief of surveillance, the most experienced tourist guide in the UMA Bonfil, the legal representative and the president of the ejidal commissariat. The chief of surveillance is in charge of keeping the territory of the UMA Bonfil free from poachers. The guide works directly with the hunters, and he is the person in charge of collecting the information about the bighorn sheep groups' location in the UMA Bonfil territory. The legal representative is in charge of the UMA legal procedures regarding the issuing of hunting permits.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

The president of the ejidal commissariat implements the agreements of the Ejido Assembly, represents and manages the UMA Bonfil, and reports to the assembly about the allocation of funds to the use of common land and their general state. The previous actors also take part in auctions by providing information describing the hunting experience at the UMA Bonfil and their opinion about the hunting permit prices during the bid. The CONANP stakeholders interviewed are the directors of the two nearest natural protected areas. In addition, we interview experts on bighorn sheep aerial surveys, hunting permit auctions and wildlife management.

Based on information provided by these stakeholders, we elicited and validated data describing state variables (variables with memory that change over the time scale considered), auxiliary variables or parameters (memoryless or constant variables), mechanisms of interaction from the hypothetical conceptual model developed in the first step, and rainfall stressors.

The bighorn sheep population in BCS is estimated every three years as part of the UMA operating rules (Lee 2003) by using aerial surveys. The bighorn sheep population data originated from the aerial survey of BCS in 2017 (open source data). Presence data are registered in geographic coordinates along with the registration of adult males of class I, II, III and IV; adult females; young males; juvenile females; and lambs. Birth and mortality rates came from the literature. Hunting permit price and revenue data were obtained from interviews in the UMA Bonfil, during which interviewees mentioned that they received approximately US$500 annually, except in 2017, when they received approximately US$757, which they considered a "Christmas bonus". Rainfall variability trends were conceptualized as shocks or stressors, and the behavior was modeled based on the

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

stakeholders' concerns and national estimates for the region (S1, S2 and S3). The scenarios were built as explained in the following section and in Appendix 1.

Scenario S1 represents a sustained decline in rainfall (prolonged water stress) as the most dramatic possible scenario; S2 represents an oscillatory rainfall pattern or water stress followed by wetter seasons as a common rainfall behavior; and S3 represents a pattern with a slight decline in historical rainfall followed by a growing positive trend as a less probable scenario but also disruptive. These scenarios are assessed as proxies of different possibilities of climate change effects.

3. Results

3.1. Conceptualization and formalization

The causal diagram represents the conceptual model, showing the interactions between variables (Fig. 3).

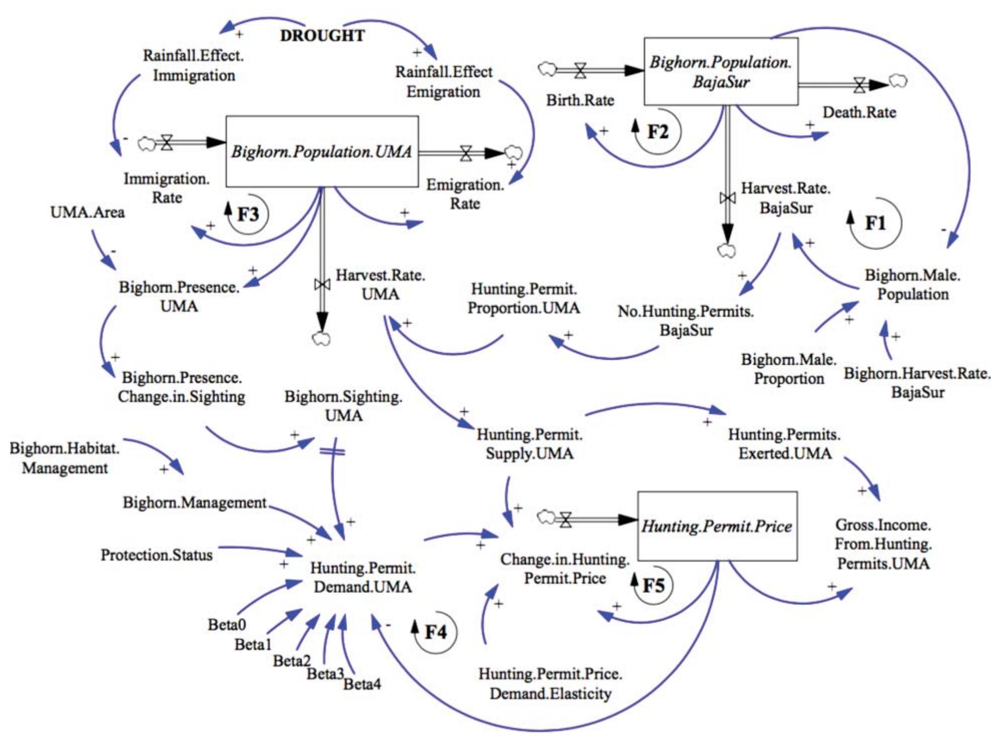


Figure 3. Conceptual model of the bighorn sheep management SES. The signs (+, -) of the arrows indicate the polarity of the relationship between variables. F1, F2, F3, F4 and F5 are the feedback loops.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

The ecological and socioeconomic subsystems interact through feedbacks among variables. The behavior of interest in this SES is described by the dynamics of the three state variables: the bighorn sheep population in BCS, the bighorn sheep population in the UMA Bonfil and the gross income from the recreational hunting activity in the UMA Bonfil. Water stress is the main stressor for this system, and the system is resilient when both subsystems maintain their structure and function. If one of the subsystems crosses the threshold and collapses, then the system is not resilient. This approach is based on Holling (1973), who assumed that a threshold or bifurcation determines the basin of attraction for a particular stressor or shock. Once we quantitatively identify the subsystems' non-desirable states, we propose different environmental policy responses in terms of bighorn sheep harvest rates to obtain socioeconomic and ecological stability in the long term. This model assesses the possibility that recreational hunting, through the auction of trophy hunting permits, contributes to society's wellbeing by creating an additional source of income for stakeholders, financing habitat conservation, satisfying consumers' demands, and improving stakeholders' quality of life through the ecosystem's stability.

3.1.1. State variables

- Ecological subsystem

State variable 1: bighorn sheep population growth rate

We considered the bighorn sheep population growth rate in BCS to be determined by the mortality rate (natural and harvest mortalities) and the birth rate. We assume that the bighorn sheep population is in a steady state based on the current harvest rate and the annual

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

natural mortality rate (0.01%)[4] reported by Roelle (2004) in the bighorn sheep population in a National Recreation Area in Montana, U.S.A.

The bighorn sheep population in the state of BCS P_{BCS} grows over time at a rate determined by the births b, deaths d, number of hunting permits approved each year (the harvest rate) p and effect of rainfall changes on births $\mathcal{E}_{\Delta R_b}$ and deaths $\mathcal{E}_{\Delta R_d}$. The estimated initial birth rate b_{Rate_0}=0.047215, and the given initial death rate d_{Rate_0} =0.01.

Births:

$$b = \mathcal{N} * b_{Rate}$$

Birth rate:

$$b_{Rate} = b_{Rate_0}\, \mathcal{E}_{\Delta R_b}(\Delta_{HistoricRainfall})$$

Deaths:

$$d = \mathcal{N} * d_{Rate}$$

Death rate:

$$d_{Rate} = d_{Rate_0}\, \mathcal{E}_{\Delta R_d}(\Delta_{HistoricRainfall})$$

where $\mathcal{N}$ is the size of the existing population in the state of BCS, and $\mathcal{E}_{\Delta R_b}$ and $\mathcal{E}_{\Delta R_d}$ are the nonlinear effects of changing rainfall on births and deaths, respectively, such that $\mathcal{E}'_{\Delta R_b}(.) > 0$, $\mathcal{E}''_{\Delta R_b}(.) > 0$, $\mathcal{E}'_{\Delta R_d}(.) < 0$, and $\mathcal{E}''_{\Delta R_d}(.) > 0$. Through these effects, the historic death and birth rates are adjusted as a function of rainfall conditions: a decrease in

[4] This assumption implies that we estimated the birth rate such that the initial birth rate was in equilibrium with the mortality rate. Modeling the bighorn sheep population in BCS in an initial steady state allows us to identify changes when we test the effects of rainfall variability.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

rainfall with respect to historical conditions increases the death rate (reduces the birth rate) to above (below) the historical estimates.

The overall equation for the bighorn sheep population in BCS is

$$\frac{\partial P_{BCS}}{\partial t} = b - d - p \qquad (1)$$

State variable 2: bighorn sheep population in the UMA

Two factors that influence demographic trends in the bighorn sheep population are nutritional status in terms of the quality and quantity of forage and predation (Mckinney et al. 2003). In this model, we simplify the dynamics of the focal scale of the bighorn sheep population by modeling the influence of rainfall on the forage. Mckinney et al., (2003) found that higher rainfall was associated with higher availability and greater differences in the mineral content of forages, which improved the nutritional status and relative abundance of the populations. Based on this information, we hypothesize that under water stress conditions, bighorn sheep populations in the state of BCS migrate from the mountainous areas where they are typically distributed to areas with more forage and water. These migrations are especially important at the socioeconomic scale because the UMA Bonfil has the right to exert the trophy hunting permits only in their territory. However, stakeholders for the UMA Bonfil are worried about prolonged water stressed periods, especially in winter, because the trophy hunting season occurs from November to December.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

We assume that the size of the bighorn sheep population in the UMA Bonfil is in a steady state based on the current harvest rate, the hypothetical emigration rate ${E_{Rate}}_0$=0.01[5] and the estimated immigration rate ${I_{Rate}}_0$=0.008385. The population size of the bighorn sheep in the UMA Bonfil P_e at time t fluctuates as a result of the immigration I, emigration E, number of hunting permits exerted each year p and effect of changing rainfall on bighorn sheep immigration $\mathcal{E}_{\Delta R_I}$ and emigration $\mathcal{E}_{\Delta R_E}$.

Immigration:

$$I = \mathcal{N} I_{Rate}$$

Immigration rate:

$$I_{Rate} = {I_{Rate}}_0 \, \mathcal{E}_{\Delta R_I}(\Delta_{HistoricRainfall})$$

Emigration:

$$E = \mathcal{N} E_{Rate}$$

Emigration rate:

$$E_{Rate} = {E_{Rate}}_0 \, \mathcal{E}_{\Delta R_E}(\Delta_{HistoricRainfall})$$

where $\mathcal{E}_{\Delta R_I}(.)$ and $\mathcal{E}_{\Delta R_E}(.)$ are the nonlinear effects of changing rainfall on immigration and emigration, respectively, such that $\mathcal{E}'_{\Delta R_I}(.) > 0$, $\mathcal{E}''_{\Delta R_I}(.) > 0$, $\mathcal{E}'_{\Delta R_E}(.) < 0$, and $\mathcal{E}''_{\Delta R_E}(.) > 0$. Through these effects, the historic immigration and emigration rates are

[5] This assumption implies that we estimated the immigration rate such that the initial emigration rate was in equilibrium with the immigration rate. Modeling the bighorn sheep population in the UMA Bonfil in an initial steady state allows us to identify changes when we test the effects of rainfall variability.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

adjusted as a function of rainfall conditions: a decrease in rainfall with respect to historical conditions increases the emigration rate (reduces the immigration rate) to above (below) the historical estimates, and an increase in rainfall has the opposite effects. The fact that these functions are nonlinear captures the notion that these opposing effects are not necessarily symmetric.

The overall differential equation for the population size of the bighorn sheep in the UMA Bonfil is the following:

$$\frac{\partial P_e}{\partial t} = I - E - p \qquad (2)$$

- <u>The socioeconomic subsystem</u>

State variable 3: hunting permit price

In the exploratory model, the human system sector has a single state variable, called the hunting permit price HPP_e, representing the result of a habitat managed sustainably (which includes watering hole maintenance, infrastructure development according to habitat conservation, keeping the mountainous area free from feral fauna and legal compliance in terms of the harvest rate) to continue carrying out the recreational hunting activity in the UMA Bonfil. The hunting permit price is the result of the price reached in an auction for that UMA. The hunting permit price also fluctuates as a result of the hunting permit supply S and demand D, where S corresponds to the number of permits available and D is the number of permits sold in an auction.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

We model the number of permits in the UMA Bonfil p_e as a function that assigns the numbers of permits in the UMA by comparing the permits allowed under the current legal harvesting rules p_{T2} and the existing population in the UMA $\mathcal{N}_e$:

Permit supply:

$$S = p_e$$

$$p_e = \begin{cases} (p_{T2})\,(p_{e_{Proportion}}), \mathcal{N}_e > (p_{T2})(\,p_{e_{Proportion}}) \\ \mathcal{N}_e, \mathcal{N}_e \leq (p_{T2})(\,p_{e_{Proportion}}) \end{cases}$$

where the proportion of hunting permits in the UMA Bonfil $p_{E_{Proportion}}$=0.173, which is estimated based on the harvest rate in BCS (40) and the number of hunting permits assigned to the UMA Bonfil (7) in the last three years. The number of permits is estimated by the government using aerial information, and in this case, we only use the result of that estimation for the area of study.

We modeled the permit demand as a linear relationship with the following expression:

Permit demand:

$$D = \beta_0 + \beta_1\,SM + \beta_2 SP + \beta_3 S_e + \beta_4 HPP_{Relative}$$

where SM is a dichotomous variable for which 1=the presence and 0=the absence of sustainable management, SP is a dichotomous variable for which 1=the presence and 0=the absence of bighorn sheep under protection in Mexico. Those two variables are constant in the case of UMA Bonfil but could vary in other UMAs. S_e is the number of bighorn sheep sighted in the UMA Bonfil per hour of flight during the aerial population survey (as a proxy for the probability of hunting a species) and $HPP_{Relative}$ is the relative price of a hunting

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

permit compared to substitutes, in this case, trophy hunting permits outside the UMA Bonfil. The relative prices in this model are inspired by the formulation of a dynamic system by Sterman (2000), in which a higher relative price increases demand and an increasing bidding price decrease the relative price.

Hunting permit relative price:

$$HPP_{Relative} = \frac{HPP_{Others}}{HPP_e}$$

where HPP_{Others}=90 (dollars) is the average price of trophy hunting permits outside the UMA Bonfil (Lee 2011), and HPP_e=90 (dollars) is the hunting permit price in the UMA Bonfil. The elasticity of supply and demand is assessed and included in the differential equation to observe the variations on the permit price.

The overall differential equation of the hunting permit price is

$$\frac{\partial HPP_e}{\partial t} = \left[\frac{1}{\varepsilon_D} * \frac{1}{D} * \frac{\partial D}{\partial t} + \frac{1}{\varepsilon_S} * \frac{1}{S} * \frac{\partial S}{\partial t}\right] \quad (3)$$

We use this specification because it is important for this context to capture the joint effects that changes in supply and demand have on the price of permits. Thus, we include the marginal change in permits' price in the state equation as a function of the elasticities in demand change ε_D (0.2) and supply change ε_S (0.175). Both parameters are hypothetical.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

3.2.Auxiliary variables

Bighorn sheep population size

To estimate the size of the population, the following equation (Lee et al. 2007) is necessary:

$$\mathcal{N} = \frac{\left(\sum \mathcal{N}_{A_m A_f J_m J_f\, L\, \phi}\right)}{\Omega} \qquad (4)$$

where $\mathcal{N}$ is the estimated population size, and $\Sigma\mathcal{N}_{A_m A_f J_m J_f\, L\, \phi}$ is the sum of all animal sightings in the categories A_m (adult males), A_f (adult females), J_m (juvenile males), J_f (juvenile females), L (lambs) and ϕ (others not classified). According to Segundo (2007), the observable population proportion for BCS is Ω=0.30. This value indicates that the population observed during the aerial survey is only 30% of the total population in BCS. In the last population aerial survey, which was carried out in December 2016 (Lee 2016), the total presence data including all categories revealed 176 animals in BCS. Therefore, the estimated bighorn sheep population size in BCS during 2016 was 586 sheep.

Bighorn sheep population presence in the UMA Bonfil

Changes in the presence of sheep in the UMA Bonfil are expressed in the following form:

$$\Delta P_e = \frac{P_e}{P_0} \qquad (5)$$

where ΔP_e is the change in bighorn sheep presence in the UMA Bonfil, P_e is the number of bighorn sheep present in each square kilometer in the UMA Bonfil and P_0 is the initial presence of sheep in the UMA Bonfil.

To estimate P_0, we used equation 4, as follows:

$$P_0 = \frac{\left(\frac{O_e}{O_{BCS}}\right)(\mathcal{N})}{A}$$

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

where O_e=38 is the total number of bighorn sheep observed in the mountainous area of the UMA Bonfil, O_{BCS}=176 is the total number of bighorn sheep observed in the mountainous area of BCS and A=5.5 is the total area of the UMA Bonfil in square kilometers. Bighorn populations are predominantly located in mountainous areas.

The number of initial sightings of sheep in the UMA Bonfil S_0 is expressed as follows:

$$S_0 = \frac{O_{BCS}}{h_{BCS}} \qquad (6)$$

where h_{BCS} is the total number of flight hours during the aerial survey in BCS.

To estimate the changes in sightings, we used the following expression borrowing from equations 5 and 6:

$$S = S_0 * \mathcal{E}(\Delta P_e)$$

where $\mathcal{E}(.)$ indicates the nonlinear effects of the change in sightings, such that $\mathcal{E}'(.) > 0$ and $\mathcal{E}''(.) > 0$. This relationship implies that if the number of bighorn sheep in the UMA is low, then it would take more hours of flight to see bighorn sheep, and if the number in the UMA is high, then it would take fewer hours of flight to see bighorn sheep, which in turn is a measure of the variation in the presence of the sheep in the area.

Bighorn sheep harvest rate

In the recreational hunting market, the trophy hunting of adult males plays a more important role than that of adult females. For this reason, adult males are classified depending on their ages: C_I, C_{II}, C_{III} and C_{IV}, with the males in C_{IV} being the oldest and most suitable to be hunted because they have a larger size and larger antlers (Lee 2003). Then, to estimate the harvest rate of this species, the equations developed by (Lee et al. 2007) are used. This method allows the harvest rate to be managed in a sustainable way

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

because it does not compromise the long-term reproductive potential of the population. The first equation is the following:

$$p_{T1} = \left[\left(\Sigma \mathcal{N}_{CI_m\, CII_m\, CIII_m\, CIV_m}\right)/\Omega\right] \varphi$$

where p_{T1} is the estimated harvest of males in all classes: class one (CI_m), class two (CII_m), class three ($CIII_m$) and class four (CIV_m). The observable population proportion for BCS is Ω=0.30, and the harvest percentage is φ=0.10 (Lee 2003) (Lee, 2003). The second equation is as follows:

$$p_{T2} = \left[\left(\Sigma \mathcal{N}_{CIII_m\, CIV_m}\right)/\Omega\right] \varphi$$

This equation uses the data from classes three ($CIII_m$) and four (CIV_m). The observable population proportion for BCS is the same (Ω=0.30), but the harvest percentage is higher (φ=0.20). Then, the lower value of the two outcomes must be used as a precautionary criterion. According to the aerial survey data from 2016, the extraction rate must be 13 permits.

To estimate the population size in the UMA Bonfil $\mathcal{N}_e$, we calculate how many bighorn sheep are in the study area per square kilometer. We use data from the aerial survey of 2016 in the following expression:

$$\mathcal{N}_e = \left(\sum \mathcal{N}_{A_m A_f J_m\, J_f\, L\, \phi}\right)/\Omega$$

where $\mathcal{N}_e$ is the number of bighorn sheep of all classes ($A_m A_f J_m\, J_f\, L\, \phi$) observed in the UMA Bonfil mountainous area (38). The observable population proportion for BCS is Ω=0.30. To estimate the presence of bighorn sheep in the UMA Bonfil, we used the following form:

$$P_e = \frac{\mathcal{N}_e}{A}$$

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

where P_e is the number of bighorn sheep per square kilometer, and $\mathcal{N}_e = 126$ is the population size in the UMA Bonfil mountainous area (where A=5.5 km^2). However, the bighorn sheep population is not static—the individuals move in the mountains. Nowak (1991) reported that the longest distance a bighorn sheep moves from its territory is 48 km. These movements were modeled in state variable 2 as immigration and emigration rates.

3.3.Exogenous stressor

Exogenous change in historical rainfall conditions

We model the effects of a changing climate on local rainfall conditions using the following stochastic exogenous stressor:

$$\Delta_{HistoricRainfall} = \mu * t + \delta * \sin(\pi * t + X) \quad (7)$$

where μ controls the long-term rainfall tendency in the model (i.e., decrease or increase), and δ and π control the amplitude and seasonal variations in precipitation in the UMA, respectively. X is a random variable defined as $X \sim F_X(x) = P(X \leq x)$ (in our analysis, we model X as $X \sim U(a, b)$) that models temporal variation in precipitation patterns in the region. Thus, we model the effect of climate change on precipitation patterns in the region as a shock or stressor wave that has a long-term tendency to affect historical precipitation conditions but for which the signal of change becomes apparent only after a sequence of seasons.

In other models, such as that of Colchero et al. (2009), the change in rainfall affected the bighorn sheep population via the probability of survival in response to different rainfall patterns. The author mentioned that this decision was based on the assumption that the bighorn sheep population under study was located on an island where there are few mobility options with which to find other sources of water and food. However, in our

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

model, the effect of the water stress patterns was modeled as changes in the immigration and emigration of the population. This decision was based on the assumption that the bighorn sheep population in BCS is in a free-living state in large mountainous areas in which bighorns can move towards regions with a greater superficial water availability and the best food options. The parameters used for simulation are presented in Appendix 1.

4.1.4 Simulation of rainfall variability in the SES and management strategies

The simulation experiment explores the implications of three different scenarios of rainfall variability (S1, S2 and S3) (Appendix 1). For each scenario, we examined the performance of two strategies: the current policy or status quo of the system and an adaptive strategy that enhances the resilience of the system. Table 1 describes the operational logic of this experiment. Each row denotes a scenario for the considered stressor. The first column indicates the three different trend stressors analyzed: S1, a prolonged water stress that stakeholders mentioned as the worrying most dramatic scenario in the region; S2, an oscillatory rainfall pattern was indicated as a desirable scenario; and S3, a growing positive rainfall was mentioned as the less probable scenario. The second column specifies the year of the simulation in which the SES subsystems under the status quo cross their thresholds and start a non-desirable negative trend. The third column points out the adaptive strategies that can help sustain a positive trend in both subsystems. This paper proposes two management strategies: a variable reduction in hunting permits and introduction of animals.

Figure 4 describes the resulting behavior for each stressor scenario. The rows describe the stressor behavior and its influence in the system's behavior under both the status quo and an adaptive decision that confers resilience (the color legend indicates the bighorn sheep

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

population percentage of change with respect to the initial conditions with 126 individuals and the grey legend indicates the hunting permit price as a proxy indicator of gross income associated with the hunting permit market). The first column displays the three stressor scenarios, and the second column displays the system's responses to each scenario, which allows for a comparison of the impact of the adaptive strategy on behavior across both subsystems.

Our analysis shows that the same extraction strategy cannot be implemented in response to the three scenarios with as it would invariably lead to negative system trends; thus, it is necessary to consider a management strategy that is adaptable to changing climatic conditions. For the proposed adaptive strategies, we identify critical thresholds for bighorn sheep populations and gross income behavior and propose changes in the management strategies based on the extraction rate and introduction of new bighorn sheep individuals to avoid a reversion to the negative outcome of the current policy.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

Table 1. Thresholds in the SES status quo (SQ1, SQ2 and SQ3) and adaptive responses (R1, R2 and R3) to the effects caused by three different stressors (S1, S2 and S3) in a SES.

Stressor (rainfall variability)	**Current policy** (ecological and economic thresholds)	**Adaptive policy** (adaptive decisions, dynamic number of hunting permits and individual's introduction)
S1 Sustained decline in rainfall (prolonged water stress)	**SQ1** *Bighorn sheep population*: Since year 2 of the simulation increase the movement to other mountainous areas, experience an increased mortality rate. *Hunting permit price*: Start decreasing from year 12 as a result of the decrease in the bighorn sheep sighting rate that causes a decline in the demand for UMA Bonfil hunting permits and pushes the hunting permit price down.	**R1** Marked reduction in the number of hunting permits (from 7 to 1) during the 30 years and escalating efforts to introduce new bighorn sheep individuals: year 1 to 10=10 bighorn sheep, year 10 to 20=5, year 20 to 30=15.
S2 Oscillatory rainfall pattern or water stress followed by wetter seasons	**SQ2** *Bighorn sheep population*: Substantial declining trend in the population from 126 to 35 from year 2 to 17 and stabilization until the end of the simulation *Hunting permit price*: Increasing prices of hunting permits from year 2 to year 10 (from 227, 000 to 330,000) as the supply of permits declines and stabilization until the end of the simulation. Income increases despite fewer permits being issued.	**R2** Harvest rate reduction (from 7 to 3 permits) during the first 20 years of the simulation and then recovers to 5 permits. In combination with the introduction of new individuals (1 per year).
S3 Slight decline in the historical rainfall followed by a growing positive trend	**SQ3** *Bighorn sheep population*: Remains in its current territory, and immigration increases. From year 17 to the end of the simulation, the population increases (from 126 to 132) *Hunting permit price*: Immigration causes an oversupply of hunting permits, which drives down the price of hunting permits. From year 18 to the end of the simulation, the gross income changes (from 227,000 to 181,000)	**R3** Greater number of hunting permits (10) helps prevent a decline in the price of hunting permits and the gross income.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

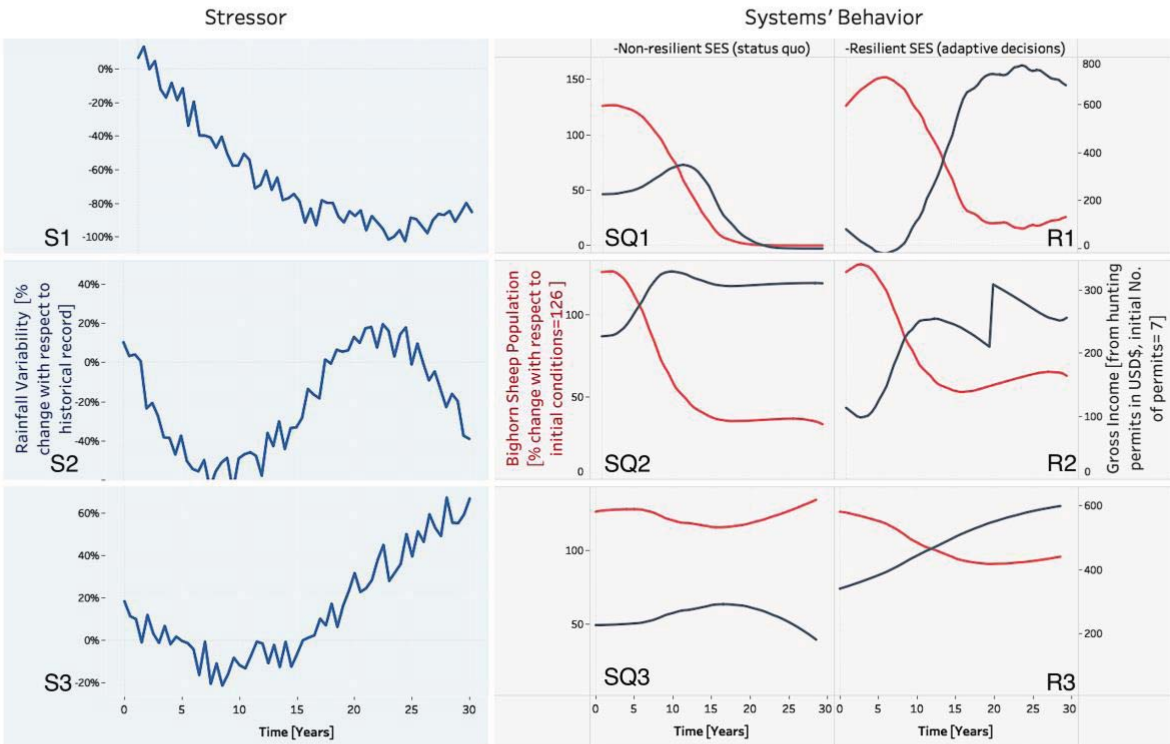


Figure 4. Adaptive responses considering the extraction rate changes and bighorn sheep individual introduction (R1, R2, and R3) to a no desirable state under the status quo (SQ1, SQ2 and SQ3) caused by the three different stressors (S1, S2, and S3).

The scenarios show that if an adaptation strategy is not implemented, then the system is not resilient, whereas under all proposed adaptation strategies, the negative trend of both subsystems decreases in the long term with changes in the current harvest rate rule and the introduction of new individuals; thus, the combination of these elements is crucial for SES stability. In particular, scenario 3 shows a resilient system because both subsystems are in good conditions. Although the current method of determining the bighorn sheep harvest rate is adequate for sustaining the bighorn population under the current regime, it does not consider potential adaptations to plausible rainfall change events. Thus, these scenarios are useful for wildlife management and policy.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

4. Discussion

The SES resilience approach is a valuable perspective that can be used to consider several dimensions of the complexity of wildlife management. Wildlife management currently defines the extraction rate based only on the total population census in BCS and does not consider the implications of rainfall variability (in the bighorn population or in the damage to managers' income), which reduces the ability of managers to prepare for and adapt to the challenges posed by this specific stressor, thus making this a non-resilient SES. The proposed model, however, allows for linkages among a species population, its habitat and management with socioeconomic outcomes. Thus, the dynamic model method is a useful tool for conceptualizing and operationalizing a social-ecological system and has been applied for fisheries (Bueno, 2012); however, this approach is not common for wildlife tourism or modelling adaptation strategies in this context. In addition, resilience is measured not only by identifying thresholds but also in terms of the maintenance of both subsystems at the same time and in terms of different adaptive strategies. This finding implies that the resilience measurement surpassed some of the challenges identified in other studies (Carpenter et al. 2001) because it is a dynamic measure that can identify thresholds and incorporate adaptative management scenarios. Moreover, this research includes the development of an interactive simulation application that can be used by stakeholders to increase SSE resilience by supporting social learning and dialogue about a shared problem among stakeholders.

The exploratory analysis for bighorn sheep suggests that a subsystem will cross its threshold in a given period of time depending on the extent and intensity of the stressor. In all cases, the implementation of an alternative management strategy is needed to observed

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

resilience. However, there are trade-offs regarding specific and general resilience (Schipper and Langston 2015). In this case, if the system becomes highly resilient to the rainfall variability stressor, then its general resilience to other events may be reduced.

The assessed adaptive measures include changes in the number of permits and the introduction of bighorn sheep individuals. However, reducing the number of hunting permits could be complemented by wildlife watching and photo tourism. From 1922 to 1964, the hunting of this species in Mexico was prohibited (Mellink 1993), which showed that such prohibition can potentially have negative results by encouraging poaching (Sandoval 1985). Moreover, wildlife watching, and photo tourism can provide a source of extra income for managers as the number of hunting permits is reduced. In East Africa, wildlife watching is one of the attractions for international tourists and accounts for the majority of their national income from tourism (Tapper 2006).

A bighorn sheep introduction program in the BCS region is a feasible strategy that was implemented with success in Tiburon Island, Mexico in 1975 (Wilder et al. 2014) and Carmen Island, BCS, Mexico (1995-2007) (Jimenez and Hernández 2010). In both efforts the introduction of bighorn sheep was successful in establishing a viable population and the species was also translocated to another region of the country. This strategy requires an evaluation of habitat quality to ensure the survival of the species. The combination of consumptive (extractive) and non-consumptive (non-extractive) tourism strategies can help in reducing the damage of water stress until rain seasonality returns to the historical normal.

The tools developed for this analysis represent an initial step towards developing integrative tools that can address specific management decisions in this type of SSE context. The current model could be improved by modelling the spatial distribution of the

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

species under climate change. A habitat suitability model might add valuable information by considering both the geographical distribution of the species and its interplay with vegetation coverage. The supply and demand functions of the model could be improved by conducting a survey of hunters to identify the determinants of hunting preferences.

Finally, we analyze resilience thresholds by modeling the induction of behavioral patterns of different water stress behavior. However, a sensitivity analysis could provide a more in-depth analysis of resilience thresholds to determine the system's responses to marginal changes in parameters values (Skonhoft 1998, Scheffer and Carpenter 2003, Scheffer et al. 2009, Schlüter et al. 2011).

Although model precision can always be increased, we believe that this paper enhances our understanding of non-lineal interactions among the bighorn population and socioeconomic wellbeing and invites a discussion among stakeholders about how management strategies could address the effects of the stressor by identifying SSE thresholds and implementing precautionary management measures.

5. Conclusions

Nonlinear interactions among socioeconomic and ecological variables for wildlife management under the conditions of climate uncertainty can be addressed by using complex systems methods. This dynamic model can identify resilience thresholds and manage SSEs by suggesting management strategies that can obtain positive responses in both subsystems. Therefore, the proposed social-ecological resilience model provides new insights for resilience and wildlife management research and environmental policies.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

6. Acknowledgments

We want to thank the National Autonomous University of Mexico (UNAM), The Sustainability Science Graduate Program and the Mexican Council of Science and Technology (CONACYT) for the PhD scholarship at UNAM under which the present investigation was developed. We also would like to thank the Protection Area of Flora and Fauna (APFF) "Valle de los Cirios" for the technical support granted during the interviews in the UMA Bonfil. Special thanks are due to everyone at UMA Bonfil for kindly granting our request and taking the time for interviews.

Funding: This work was supported by the Programa de Apoyo a Proyectos de Investigación Tecnológica (PAPIIT) PAPIIT-UNAM-IN301516.

7. References

Adams, W. M., B. Dickson, H. T. Dublin, and J. Hutton. 2009. Recreational Hinting Conservation and Rural Livelihoods. Wiley-Blackwell, Sussex.

Avila-Foucat, V. S., and E. Pérez-Campuzano. 2015. Municipality Socioeconomic Characteristics and the Probability of Occurrence of Wildlife Management Units in Mexico. Environmental Science & Policy **45**:146-153.

Berkes, F., J. Colding, and C. Folke. 2003. Building Capacity to Adapt to Change: The context. Pages 1-20 *in* F. Berkes, J. Colding, and C. Folke, editors. Navigating Social-Ecological Systems. Cambridge University Press, Cambridge.

Brown, E. D., and B. K. Williams. 2015. Resilience and Resource Management. Environ Manage **56**:1416-1427.

Bueno, N. P. 2012. Assessing the resilience of small socio-ecological systems based on the dominant polarity of their feedback structure. System Dynamics Review **28**:351-360.

Carabias, J., J. Sarukhan, J. de la Maza, and G. Carlos. 2010. Patrimonio Natural de México. Cien casos de éxito. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, Mexico.

Carpenter, S., and L. Gunderson. 2001. Coping With Collapse: Ecological and Social Dynamics in Ecosystem Management. BioScience **51**:451-457.

Colchero, F., R. A. Medellin, J. S. Clark, R. Lee, and G. G. Katul. 2009. Predicting Population Survival Under Future Climate Change: Density Dependence, Drought and Extraction in an Insular Bighorn Sheep. J Anim Ecol **78**:666-673.

CONAGUA. 2018. Estadísticas del Agua en México. Comisión Nacional del Agua-Secretaría del Medio Ambiemte y Recursis Naturales, Mexico.

Epps, C., D. McCoullough, J. D. Wehausen, V. C. Bleich, and J. Rechels. 2004. Effects of Climate Change on Population Persistence of Desert-Dwelling Mountain Sheep in California. Conservation Biology **18**:102-113.

Filatova, T., J. G. Polhill, and S. van Ewijk. 2015. Regime Shifts in Coupled Socio-environmental Systems: Review of Modelling Challenges and Approaches. Environmental Modelling & Software **75**:333-347.

Folke, C. 2016. Resilience. Ecology and Society **21**:44.

Folke, C., S. Carpenter, B. H. Walker, M. Scheffer, T. Chapin, and J. Rockström. 2010. Resilience Thinking Integrating Resilience, Adaptability and Transformability. Ecology and Society **15**:20.

Forrester, J. 1961. Industrial Dynamics. M. I. T. Press, Cambridge.

Gotts, N. M., G. A. K. van Voorn, J. G. Polhill, E. d. Jong, B. Edmonds, G. J. Hofstede, and R. Meyer. 2018. Agent-based Modelling of Socio-Ecological Systems: Models, Projects and Ontologies. Ecological Complexity: https://doi.org/10.1016/j.ecocom.2018.1007.1007

Hauptfeld, R. S., and J. M. Kershner. 2014. Sierra Nevada Individual Species Vulnerability Assessment Briefing: Bighorn Sheep. EcoAdapt.org, USA.

Holling, C. S. 1973. Resilience and Stability of Ecological Suystems. Annual review of Ecology and Systematics **4**:1-23.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

Holling, C. S. 2001. Understanding the Complexity of Economic, Ecological, and Social Systems. Ecosystems **4**:390-405.

Ivanova, A., and A. Gámez. 2012. Plan Estatal de Acción ante el Cambio Climático para Baja California Sur. CIB, CICESE, CONACYT, INE, CICIMAR-IPN, SEMARNAT, BAJA CALIFORNIA SUR-GOBIERNO DEL ESTADO, Mexico.

Jimenez, S. D., and M. C. Hernández. 2010. Conservation Program of the Desert Bighorn Sheep (Ovis canadensis weemsi) in South Baja California, Mexico. Galemys **22**:447-468.

Johnson, T., and D. Swift. 2000. A Test of a Habitat Evaluation Procedure for Rocky Mountain Bighorn Sheep. Restoration Ecology **8**:47-56.

Jones, B. T. B. 2009. Community Benefits From Safari Hunting and Related Activities in Southern Africa. Pages 157-177 *in* B. Dickson, J. Hutton, and W. M. Adams, editors. Recreational Hinting Conservation and Rural Livelihoods. Wiley-Blackwell, Sussex.

Lade, S. J., A. Tavoni, S. A. Levin, and M. Schlüter. 2013. Regime Shifts in a Social-ecological System. Theoretical Ecology **6**:359-372.

Leader-Williams, N. 2009. Conservation And Hunting: Friends or Foes. Pages 9-24 *in* B. Dickson, J. Hutton, and W. M. Adams, editors. Recreational Hunting Conservation and Rural Livelihoods. Wiley-Blackwell.

Lee, R. 2003. A Review of Recent Wild Sheep Surveys in Baja California Sur, Mexico. Desert Bighorn Council Transactions **43**:43-46.

Lee, R. 2011. Economic Aspects and the "Market" for Desert Bighorn Sheep. Page 23 Desert Bighorn Council Transactions.

Lee, R. 2016. Monitoreo Aéreo de la Población de Borrego Cimarron en Baja California Sur (2016). Non published technical report.

Lee, R., R. A. Medellin, R. E. Rominger, M. J. González, T. A. Espinoza, J. M. Segundo, C. Manterola y Piña, and F. M. Colchero. 2007. Borrego Cimarrón (Ovis canadensis). Pages 222–238 Talleres sobre conservación y uso sustentable de aves y mamíferos silves-tres, en relación con las Unidades de Conservación y Manejo de Vida Silvestre (UMA) en México. INECC-SEMARNAT-UPC, Mexico.

Levin, S., S. Barrett, S. Aniyar, W. Baumol, C. Bliss, B. Bolin, P. Dasgupta, P. Elhlrich, C. Folke, I.-M. Gren, C. S. Holling, A. Jansson, B.-O. Jansson, D. Martin, C. Perrings, and E. Sheshinski. 1998. Resilience in Natural and Socioeconomic Systems. Environment and Development Economics:221-262.

Mckinney, T., S. Boe, and J. C. deVos. 2003. GIS-Based Evaluation of Escape Terrain and Desert Bighorn Sheep Populations in Arizona. Wildlife Society Bulletin **31**:1229-1236.

Mellink, E. 1993. Biological Conservation of Isla de Cedros, Baja California, Mexico: Assessing Multiple Threats. Biodiversity and Conservation **2**:62-69.

Nowak, R. M. 1991. Walker's Mammals of The World. The Johns Hopins University Press, Baltimore, Maryland, EUA.

Polhill, J. G., T. Filatova, M. Schlüter, and A. Voinov. 2015. Modelling Systemic Change in Coupled Socio-environmental Systems. Environmental Modelling and Software:1-15.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

R Core Team. 2014. R: A language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
Roelle, J. 2004. Bighorn Sheep Demography and Population Modeling, Bighorn Canyon National Recreation Area, Wyoming and Montana, 2000–2002. Pages 37-67 *in* K. A. Schoenecker, editor. Bighorn Sheep Habitat Studies, Population Dynamics, and Population Modeling in Bighorn Canyon National Recreation Area, 2000–2003. Biological Resources Discipline, Open File Report 2004-1337, Virginia.
Sandoval, A. V. 1985. Status of Bighorn Sheep in the Republic of Mexico. Pages 86–94 *in* M. Hoefs, editor. Wildsheep; distribution, abundance, managementand conservation of the wild sheep of the worldand closely related mountain ungulates. Northern Wild Sheep and Goat Council Special Report, Canada.
Scheffer, M., J. Bascompte, W. Brock, V. Brovkin, Carpenter, Stephen, V. Dakos, H. Held, E. van Nes, M. Rietkerk, and G. Sugihara. 2009. Early-warning Signals for Critical Transitions. Nature **461**:53-59.
Scheffer, M., and S. R. Carpenter. 2003. Catastrophic Regime Shifts in Ecosystems: linking Theory to Observation. Trends in Ecology & Evolution **18**:648-656.
Schipper, L., and L. Langston. 2015. A Comparative Overview of Resilience Measurement Frameworks: Analyzing Indicators and Approaches. Overseas Development Institute London.
Schlüter, M., J. Hinkel, P. W. G. Bots, and R. Arlinghaus. 2014. Application of the SES Framework for Model-based Analysis of the Dynamics of Social-Ecological Systems. Ecology and Society **19**:36.
Schlüter, M., H. Leslie, and S. Levin. 2009. Managing Water-use Trade-offs in a Semi-arid River Delta to Sustain Multiple Ecosystem Services: A Modeling Approach. Ecological Research **24**:491-503.
Schlüter, M., R. R. J. McAllister, R. Arlinghaus, N. Bunnefeld, K. Eisenack, F. Hölker, E. J. Milner-Gulland, and B. Müller. 2011. New Horizons for Managing the Environment A Review of Coupled Social-Ecological Systems Modeling. Natural Resource Modeling **23**:219-272.
Schlüter, M., and C. Pahl-Wostl. 2007. Mechanisms of Resilience in Common-pool Resource Management Systems: an Agent-based Model of Water Use in a River Basin. Ecology and Society **12**:4.
Segundo, G. J. M. 2007. Resultados de los Monitoreo Aéreo para el Borrego Cimarrón Llevados a Cabo en los Estados de Baja California Sur y Sonora Durante Octubre y Noviembre del 2006. Secretaría de Medio Ambiente y Recursos Naturales / Dirección General de Vida Silvestre. Non-published Tecnical Report. México D. F. Page 283 *in* O. Sánchez, P. Zamorano, E. Peters, and H. Moya, editors. Temas Sobre Conservación de Vertebrados de Vida Silvestre. 2011. INECC-SEMARNAT, Mexico.
Skonhoft, A. 1998. Resource Utilization, Property Rights and Welfare— Wildlife and the Local People. Ecological Economics **26**:67-80.
Smith, T., J. Flinders, and D. Winn. 1991. Habitat Evaluation Procedure for Rocky Mountain Bighorn Sheep in the Intermountain West. Great Basin Naturalists **51**:205-225.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

Sterman, J. D. 2000. Business Dynamics Systems Thinking and Modeling for a Complex World. Jeffrey J. Shelsfud, USA.

Tapper, R. 2006. Wildlife Watching and Tourism: A Study on the Benefits and Risks of a Fast Growing Tourism Activity and its Impacts on Species. United Nations Environment Programme (UNEP) / Convention on Migratory Species (CMS).

Villarreal, G. J. G. 2012. Introducción al Manejo y Aprovechamiento Sustentable de la Fauna Silvestre en Ranchos Ganaderos Diversificados. SAGARPA, Mexico.

Walker, B. H., C. S. Holling, S. Carpenter, and A. Kinzig. 2004. Resilience, Adaptability and Transformability in Social– ecological Systems. Ecology and Society **9**:5.

Walker, B. H., and D. Salt. 2012. Resilience Practice: Building Capacity to Absorb Disturbance and Mantain Function. Island Press, Washigton, DC.

Wilder, B. T., J. L. Betancourt, C. W. Epps, R. S. Crowhurst, J. I. Mead, and E. Ezcurra. 2014. Local Extinction and Unintentional Rewilding of Bighorn Sheep (Ovis canadensis) on a Desert Island. PLoS One **9**.

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

Appendix 1.

Simulations with three different rainfall variability trends

We conducted a series of experiments to analyze the potential effect of climate change in the UMA Bonfil. Using equation 7, we analyze 3 different rainfall variability trends:

Archetype I $\mu = -0.035, \delta = 0.4, \pi = 0.19$

Archetype II $\mu = -0.025, \delta = 0.38, \pi = 0.12$

Archetype III $\mu = -0.009, \delta = 0.55, \pi = 0.16$

using the following parameterization:

$$\mathcal{E}_{\Delta R_b} = 0.5 + 1/\left(1 + e^{[-6(\Delta_{HistoricRainfall} - 1)]}\right)$$

$$\mathcal{E}_{\Delta R_d} = 100e^{-4.6 * \Delta_{HistoricRainfall}}$$

$$\mathcal{E}_{\Delta R_I} = 0.5 + 1/\left(1 + e^{[-6(\Delta_{HistoricRainfall} - 1)]}\right)$$

$$\mathcal{E}_{\Delta R_E} = 100e^{-4.6 * \Delta_{HistoricRainfall}}$$

and the following initial conditions:

$Bighorn\ sheep\ population\ in\ BCS\ (\mathcal{N}) = 586\ [number\ of\ bighorns]$

$Bighorn\ sheep\ population\ in\ ejido\ (\mathcal{N}_e) = 126\ [number\ of\ bighorns]$

$Hunting\ permit\ price\ from\ ejido\ (HPP_e) = 70\ [USDx1000]$

$Time\ step = 0.5\ [years]$

$Time\ span\ (t) = 30\ [years]$

Zamora-Maldonado, H., V. S. Avila-Foucat; V. Sánchez-Sotomayor & R. Lee. 2021. Social-ecological Resilience Modeling: Water Stress Effects in the Bighorn Sheep Management System in Baja California Sur, Mexico. Ecological Complexity 45 https://doi.org/10.1016/j.ecocom.2020.100884

IV. CAPÍTULO 3

Modeling Climate Change Impacts on Bighorn Habitat Suitability in Mexico and Implications for its Management

Abstract

Exploratory analysis for habitat suitability in the future is essential to inform management and conservation strategies of wildlife species today. We used an ecological niche modeling approach to examine present climatic niche and potential distribution of bighorn sheep (*Ovis canadensis*) populations in Mexico and climate change effects on its potential future habitat suitability and distribution. Niche models were built with 1,158 georeferenced occurrence records and uncertainty of climate change was addressed by exploring possible scenarios under four Representative Concentration Pathways (RCPs) (2.6, 4.5, 6.0 and 8.5) and four different General Circulation Models (GCM) in a time span of 20 years (2041-2060). This study attempts to lay out numerous scenarios of change in rainfall and temperature to integrate the uncertainty associated and point out its importance in the exploration of possible implications in the habitat suitability, conservation and management strategies of the bighorn at a regional scale. Our results showed that models were generally robust with an AUC average value of 0.9887. Particularly, the incidence of precipitation events is important under driest and warmer conditions of the year, and extreme temperatures has a negative influence. We found that the suitable area of the bighorn sheep in future projections changed distinctly under different GCMs. Hence, potential habitat suitability in the future is a multifactorial outcome. When current protection strategies on public and private lands are inadequate for the conservation of target taxa given projected climate impacts, niche models may be most useful in directing attention toward locations that may be suitable locations for conservation under future conditions. This analysis can be extended by considering a wider range of climatic projections or GCMs, multiple species, exploring strategies that employ an array of environmental policy options and potential for learning that ease the reframing and refocusing of goals with which the wildlife management community may need to engage in the face of the climate change uncertainty challenge.

Keywords

Ecological niche modeling, climate change uncertainty, wildlife management, bighorn sheep

1. Introduction

For wildlife managers, conserving species in the face of climate change can be a complex endeavor. As conditions change on the ground, the landscapes that species use now may be different from the ones are available or they choose in the future. There are a number of ways that climate change is beginning to impact wildlife. Temperature increases and changes in historical precipitation patterns can directly affect species depending on their physiology and tolerance of environmental changes. Climate change can also alter a species' food supply or its reproductive timing, indirectly affecting its fitness. Therefore, future climate patterns will likely have strong impacts on species' geographic distributions (Garcia et al., 2014). Thus, preserving ecosystems and species in their current locations may become increasingly difficult because climate change is emerging as the greatest uncertain conservation challenge of the future (García et al., 2016; Hoegh-Guldberg et al., 2018). Analyzing these effects is an important step in developing management strategies that can help species to survive in a changing climate.

Climate change can impact ecosystems directly and indirectly. Direct impacts include ecosystems' seasonal changes in rainfall and temperature and indirectly impacts include other induced disturbances such as fires, floods and droughts (Peterson et al, 2015). Moreover, it is suggested that all those impacts will be spatially and economically differentiated and that wildlife-dependent households will be particularly threatened (Adger, 2010; Robinson & Bennett, 2001). Therefore, there are economic losses associated with floods, droughts, and wildfires. The effects of climate change on biological species can be estimated by comparing temperature and precipitation patterns and trends in relation to species' distributional shifts (Peterson & Anamza, 2015). In this regard, ecological niche modeling (ENM) and Species Distribution Modeling (SDM) have been used as a tool with which to assess potential impacts of climate change processes on species' distribution.

ENM/SDM is a suite of methods that characterizes the suitable environmental conditions that allow species to persist (i.e., its ecological niche). The model of the species' ecological niche can be projected to the geographic space to produce a map that represents the distribution of such suitable conditions, which can be further projected to alternative scenarios, for instance, climate change scenarios, to produce potential distribution maps under such conditions.

A particularly symbolic game species in North America is the bighorn sheep. A revision made in 2018 by the Wild Sheep Foundation (2020) of the current management plans for bighorn sheep in different parts of Mexico, USA and Canada, showed that only two of them mentioned climate change as an important variable to consider in the management plans. However, they do not mention how to face this challenge. The main reason is that climate change is uncertain. The uncertainty associated to climate change increases the challenge for wildlife conservation planners. In particular, making habitat site selection more difficult.

In Mexico, economically important wildlife species are managed by a federal program called Units for the Conservation, Management and Sustainable Use of Wildlife (UMAs), which are policy instruments for conservation and management of flora and fauna species in Mexico. This conservation and management scheme covers a larger extension than natural protected areas (Avila-Foucat & Pérez-Campuzano, 2015). The policy aims to generate income for managers in the community and private lands derived from the conservation of species and their habitat. UMAs are operated under a management plan approved by the Secretariat of Environment and Natural Resources (SEMARNAT) to harvest individuals for which there is a continuous monitoring of habitat and populations. UMAs are either extensive UMAs (species are managed in wild conditions) or intensive UMAs (species are managed in enclosures or greenhouses). In the extensive UMAs, population numbers are estimated from field sampling. Bighorn sheep populations in Mexico are managed in extensive UMAs and they have been estimated by both aerial and terrestrial surveys. Bighorn sheep have been authorized to be managed in Mexico in the states of Baja California Sur, Sonora, Coahuila, Nuevo Leon, and Chihuahua since 1996 to date. The Official Mexican Regulation (NOM) 059-ECOL-1994 considers the subspecies (*O. c. weemsi*) as subject to special protection and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) includes this subspecies in Appendix II.

This species has not always been managed in the Mexican territory. At the end of the 1800s, the Mexican federal government initiated a series of wildlife monitoring and found decimated populations of bighorn sheep, so, at the beginning of the twentieth century, the hunting of the species throughout the Mexican territory was prohibited. This ban restricted sport and commercial hunting but had very little effect on subsistence and opportunistic hunting. In 1964, with the idea of evaluating the populations of sheep for economic purposes, the hunts were launched. They sought to increase the knowledge of the species while making a measured hunting use. Ten years later, the Bighorn Sheep Mexican Program was launched, an estimated of 900 individuals in Mexico were hunted in the following 15 years with successful economic results for the hunting organizers, but without benefit for the local communities. In 1996, thanks to the possibilities offered by the Biosphere Reserve scheme, in conjunction with the UMAs and the Foundation for North American Wild Sheep (FNAWS), the Bighorn Sheep Mexican Program began in ejido (i.e., a communal land tenure category) Alfredo Vladimir Bonfil, located in the El Vizcaino Biosphere Reserve, in Baja California Sur. The main goal was to implement a conservation program that was self-sustaining in the long term. The hypothesis proposes that if the sustainable management of natural resources leaves profits in local communities, and not in the intermediary, it will have a positive effect on the resources and habitat conservation. Under optimum conditions of sustainable management, a bighorn specimen can reach a market value in the order of $65,000 USD or more, so that conservation can become an attractive business scheme for a community or even, in the long term, for a region. The Bighorn Sheep Mexican Program includes three lines of action to be developed by both the Program staff and the Reserve's management: 1) Participatory monitoring and surveillance; 2) Management of habitat and populations, and 3) Environmental education. A bank trust was established for the management of the economic resources generated by the program and all financial decisions are made in the plenary session of a Technical Committee, made up of federal, state, municipal and ejidal authorities. The program is committed to applying the resources obtained by hunting to the conservation of natural resources and local wellbeing.

Here, we explore climate change effects on wildlife habitat suitability and show how this information can be used to guide management decisions under future climate scenarios. This study describes an application of ENM in the exploration of future climate change scenarios and its possible implications in conservation and management of Ovis canadensis, an important game specie in North America. In this exploratory analytic research, the problem can be simplified in order to better understand the characteristics to explore and experiment with the analytic approach. Thus, this study focuses on three subspecies (*O. c. mexicana, O. c. cremnobatres, O. c. weemsi*) distributed in northern Mexico, which represents one of the most profitable game species in the country, with annual revenues of $2, 657, 000 USD in BCS (2011). Uncertainty about future climate presents a challenge both for scenario development of the ecological impacts of climate change and for sustainable management of natural resources (Wang et al., 2012). Often, projections about climate change impacts are based on a single climate change scenario or small number of GCMs and GHG emission scenario combinations used to represent a wide array of equally plausible future climates (IPCC, 2007b). These strategies reduce computational effort and simplify interpretation for decision-makers; however, relying on only one or few arbitrarily selected climate change scenarios increases the likelihood of producing biased projections. To incorporate climate uncertainty in this analysis, we first projected the future potential distribution of bighorn sheep niche using each of a selected subset of climate change scenarios separately; then, we combined the results of multiple projections into a single 'consensus' map on which each pixel was identified as the environmental conditions most frequently projected across all climate change scenarios.

The socioeconomic and wildlife population dynamics analysis in the context of climate change attempts to inform managers about certain constrains in their current and future management strategies and the potential outcomes of alternative policy decisions prior to acting. These will enable adaptive management strategies oriented to wildlife conservation by implementing adaptive policies for the sustainability in the wildlife agenda.

2. Methods

2.1.Study Area

This study was conducted in northwestern Mexico. However, the bighorn sheep ranges widely in western Canada, western United States, and northern Mexico (Figure 1). The original distribution of this species in Mexico was in the steep hills of the states of Baja California (1), Baja California Sur (2), Sonora (3), Chihuahua (4), Coahuila (5), and Nuevo Leon (6) (Figure 1, map 2012). (Medellín et al, 2005). However, populations from the states of Chihuahua, Coahuila, and Nuevo Leon were eradicated in the last century, and the remaining populations in other areas of Mexico are highly fragmented (Ceballos & Oliva, 2005). Nowadays, the bighorn populations at Sonora, Baja California Sur and Baja California are reported to be stable (Lee, 2003).

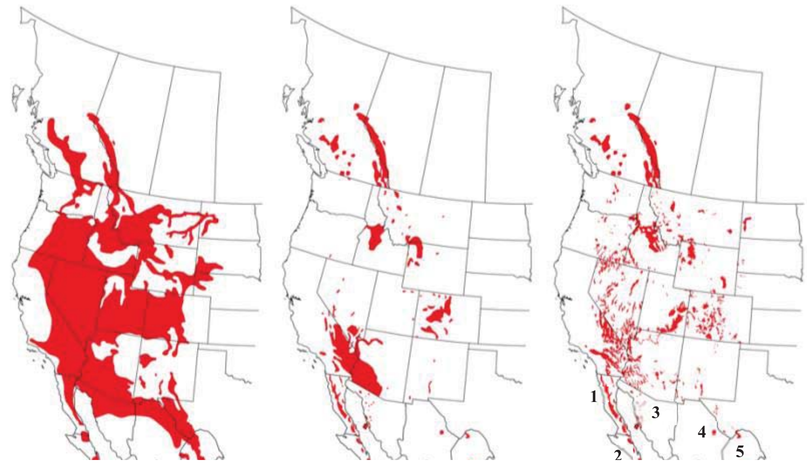


Figure 4. *Historic distribution of bighorn sheep.* Source: Wild Sheep Foundation

1850 **1960** **2012**

Figure 5. *Historic distribution of bighorn sheep.* Source: Wild Sheep Foundation

2.2.Input data

Ecological niche models need two types of data to calculate habitat suitability; a set of georeferenced locations where the species has been detected and a set of quantitative raster maps describing the environmental conditions under which the target species lives. This study uses climatic variables that are among the most important factors that drive species' distribution (Grinnell, 1917; Guisan et al., 2013), especially at large spatial extents, as they have a direct influence on the behavior and physiology of organisms. They are particularly important for plants, which cannot evade adverse weather by sheltering or migrating. In this study, animals' response to climatic variables is partly indirect through correlations with the vegetation used as food or shelter.

Occurrence data for the bighorn sheep were obtained from two sources including open access information from aerial surveys in Mexico (1994-1999, 2016) and from the Global Biodiversity Information Facility web data base (GBIF.org). Occurrence data were filtered from f 1994 to the present (2020) and only the subspecies *O. c. mexicana, O. c. cremnobatres, O. c. weemsi* were included. The occurrence records were spatially verified to ensure that they were removed from the database, resulting in 280 georeferenced records. The calibration area (the M region *sensu*

Barve et. al., 2011) for these subspecies distributed in Mexico based on the ecoregion in which they (Escobar-Flores et al., 2015) as these units represent geographic barriers for dispersal of several species. For O. canadensis in Mexico, the ecoregions selected were California, Baja California, Sonorense, Altiplano Norte, Tamaulipeca and Sierra Madre Occidental.

Nineteen bioclimatic layers corresponding to annual, seasonal, and extreme aspects of the climatic patterns that offer a better high-resolution climate data fit than the simple monthly or yearly averages were downloaded from Chelsa (https://chelsa-climate.org) database for the current and future period using the time series (1979-2013) and (20141-2060) (Karger et al., 2018) (Table 1). All layers were downloaded in 30 arc-sec resolution and clipped using the library in R for the calibration area. Future climate models or GCMs (General Circulation Models) use information described in scenarios of greenhouse gas (GHG) emissions or RCPs (Representative Concentration Pathways) to get climate change scenarios. Climate layers were cropped to the M region. The uncertainty of climate projections was explored using four different RCPs (2.6, 4.5, 6.0, 8.5), in conjunction with four GCMs (Table 2) in a time span of 20 years (2041-2060). The RCPs reflect potential emission levels of greenhouse gases projected over the next few decades and ranged from optimistic scenarios of emission reductions after 2020 (RCP 2.6) to assumptions that emissions will continue to increase until 2100 (Weyant et al., 1996)

Table 2. *Bioclimatic variables used in the ecological niche modeling of Ovis canadensis in Mexico*

VARIABLES	UNITS
Bio1 Annual Mean Temperature	1/10 ^{0}C
Bio2 Mean Diurnal Range	1/10 ^{0}C
Bio3 Isothermality	*100
Bio4 Temperature Seasonality	*100
Bio5 Max Temperature of Warmest Month	1/10 ^{0}C
Bio6 Min Temperature of Coldest Month	1/10 ^{0}C
Bio7 Temperature Annual Range	1/10 ^{0}C

Bio8 Mean Temperature of Wettest Quarter	1/10 ^{0}C
Bio9 Mean Temperature of Driest Quarter	1/10 ^{0}C
Bio10 Mean Temperature of Warmest Quarter	1/10 ^{0}C
Bio11 Mean Temperature of Coldest Quarter	1/10 ^{0}C
Bio12 Annual Precipitation	mm
Bio13 Precipitation of Wettest Month	mm
Bio14 Precipitation of Driest Month	mm
Bio15 Precipitation Seasonality	Coefficient of variation *100
Bio16 Precipitation of Wettest Quarter	mm
Bio17 Precipitation of Driest Quarter	mm
Bio18 Precipitation of Warmest Quarter	mm
Bio19 Precipitation of Coldest Quarter	mm

2.3.Data Processing

Variables pre-selection

Several highly correlation variables were used as the training part sets to develop the model, which may disturb the results of variables importance analysis, even the model performance. Thus, we use the multi-collinearity test (by Pearson Correlation Coefficient) to analyze the cross-correlation. If the Pearson Correlation Coefficient of two variables $|r| > 0.85$, which meant they are highly correlation and one of them should be excluded. The one with high important gain should be retained, as it contains more helpful information to model contribution.

The covariate correlation analysis was conducted with the R environment (standard R platform, there is no need to use a package) for assessing multicollinearity among environmental variables. When two variables had a Pearson correlation coefficient $|r| > 0.85$, only one of the pair was selected for model development, based on the predictor, relative importance of each variable and expert knowledge (Table 3).

The predicted model was run for the present time 1979-2013 and then projected for 2041-2060 in the different RCPs and GCMs. The resulted data and its visualization for future exploratory scenarios was developed using Tableau version 2018.3, a software for interactive data visualization.

Table 3. *Modeling center or groups that developed the different General Circulation Models (GCMs) and the Representative Concentration Pathways (RCPs) used in the exploration of future changes in the bighorn sheep niche.*

Modeling Center or Group	**Model Name**	**ID**	**RCPs**
Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNMRN-CM5	CM5	**RCP 2.6**: assumes that global annual GHG emissions (measured in CO 2-equivalents) peak between 2010–2020, with emissions declining substantially thereafter
College of Global Change and Earth System Science, Beijing Normal University	BNU-ESM	ESM	

LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University	FGOALS-g2	g2	**RCP 4.5**: peak around 2040, then decline
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-Mk3.6.0	Mk3	**RCP 6.0**: emissions peak around 2080, then decline.
		CM	**RCP 8.5**: emissions continue to rise throughout the 21st century
		CMS	

To explore the uncertainty among the different GCMs, we used a raster layer (polygons) of ejidos in Mexico. Using the ejidos polygons as a reference, we were able to identify the areas with high suitability for the bighorn sheep. The identification of these areas is important in terms of policy intervention in the conservation of this species. In Mexico, bighorn sheep's UMAs are arranged by ejidos and so does the financial support from the government for habitat management and species conservation. We obtained the suitability values by ejido and compared changes in the different maps obtained with the average of GCMs and the different RCPs.

3. Results

3.1. Environmental variables selection

A covariate correlation analysis showed that 10 environmental variables best explain the bighorn sheep presence. The variables' Pearson correlation coefficients threshold was $|r| \geq 0.85$

Table 3. *Climate variables used for modeling climatic niche.*

VARIABLES	UNITS
Bio1 Annual Mean Temperature	1/10 ^{0}C
Bio2 Mean Diurnal Range	1/10 ^{0}C
Bio3 Isothermality	*100
Bio4 Temperature Seasonality	*100
Bio5 Max Temperature of Warmest Month	1/10 ^{0}C
Bio6 Min Temperature of Coldest Month	1/10 ^{0}C
Bio7 Temperature Annual Range	1/10 ^{0}C
Bio8 Mean Temperature of Wettest Quarter	1/10 ^{0}C
Bio9 Mean Temperature of Driest Quarter	1/10 ^{0}C
Bio10 Mean Temperature of Warmest Quarter	1/10 ^{0}C
Bio11 Mean Temperature of Coldest Quarter	1/10 ^{0}C
Bio12 Annual Precipitation	mm

Bio13 Precipitation of Wettest Month	mm
Bio14 Precipitation of Driest Month	mm
Bio15 Precipitation Seasonality	Coefficient of variation *100
Bio16 Precipitation of Wettest Quarter	mm
Bio17 Precipitation of Driest Quarter	mm
Bio18 Precipitation of Warmest Quarter	mm
Bio19 Precipitation of Coldest Quarter	mm

The bolded variables were used in modeling.

Model settings

The Maxent method is based on presence data and a random sampling of background points in the study region.

The MaxEnt model was run with 5 replicates and 25% of random test percentage, a maximum number of backgrounds points of 8000, the maximum iterations as 500, and a regularization parameter value of 0.5, and cloglog output format. The random test percentage was 25%, which means that 75% of the total database was used as the random sample to train the model, and other 25% of the total database was used to test the model predictions. To avoid over-fitting of the test data, we set the regularization multiplier value as 0.5. The output format was default "cloglog" transform, which has the stronger theoretical justification than the logistic transform (Phillips et al., 2017). This study used linear, quadratic, product, threshold, and hinge feature classes (auto features) based on the number of sample sizes (Phillips & Dudík, 2008). Phillips and Dudík (2008) classified the features for sample sizes: auto features setting for more than 80 records, quadratic and hinge setting for 15–79 record, linear and quadratic for 10–14 record, and linear setting for sample sizes fewer than 10 records. The Jackknife test (systematically leaving out each variable) was used to assess the contribution and the importance of each 9 bioclimatic variables to the model (Table 4).

The ENM established a relationship between the bighorn sheep occurrence and predictor variables and estimates the present and future climatic niche for the bighorn sheep in Mexico. The goodness-of-fit test of Maxent model was evaluated by the area under the threshold-independent receiver operating characteristic curve (AUC) and TSS (Allouche et al., 2006) based on 5-fold cross-validation method. A suitable habitat map for *Ovis canadensis* was produced by utilizing the AUC weight averages of the 5 cloglog output maps produced by 5-fold cross-validation, in which the relative suitability ranged from 0 to 1. The performance of the final model was measured in terms of average AUC (the area under the receiver-operating-characteristic curve) ranging between 0.5 and 1 and TSS ranging between -1 and 1. The AUC and TSS close to 1 means that the predicted model performs well (Feria et al., 2010). The value of AUC varied from 0 to 1, among which, that of 0.5 suggests that the models show no predicting capability, while that of >0.7 represents that the models are acceptable

The average AUC value of niche models from cross validation (5 k-fold) was 0.9887, indicating a high discrimination accuracy between presence and background. Conversely, the TSS parameter was (0.4955).

Figure 2 shows that the bighorn sheep habitat suitability is currently restricted to the northwest Mexico (Baja California, Baja California Sur, and Sonora, including the Tiburon Island). The map only shows high suitability data (0.4 to 0.99) under the current climate conditions. Baja California (Figure 2, number 1) has the mayor number of ejidos (35) with a high habitat suitability index. Baja California Sur (figure 2, number 2) has 12 ejidos with an important suitability, mainly ejido Bonfil. Sonora (Figure 2, number 3) is the third state with an important habitat suitability in five ejidos, including the Tiburon Island.

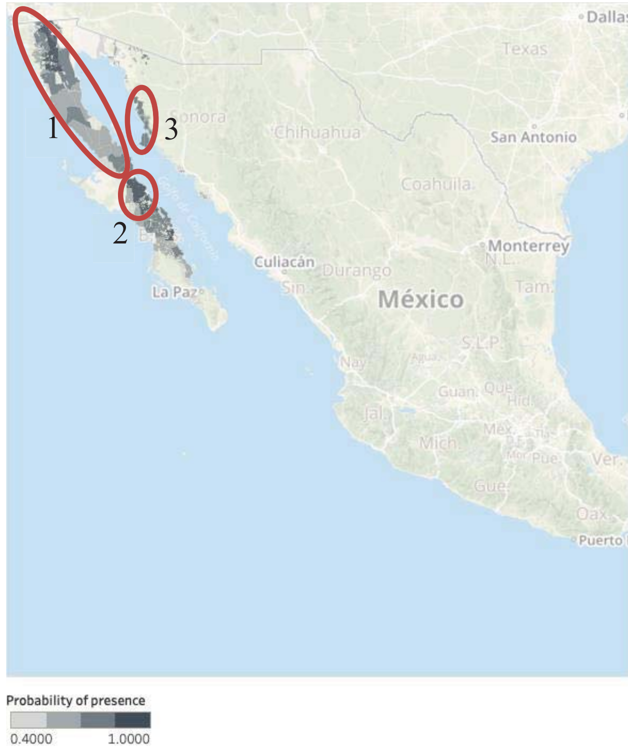


Figure 6. *Bighorn sheep habitat suitability in Mexico under current bioclimatic conditions (Chelsa time series 1979-2013)*

The influence of GCMs on ENM matters, especially when the aim of the study is policy oriented and wildlife management plans are developed based on these. In this example, we can see that the habitat suitability index changed among GCMs. Then, to decide which future is more likely, one option to deal with uncertainty is the exploration of all possible futures. This implies the use of computational approaches that help in the analysis of large amounts of data. In this study we explored six different GCMs to explore its associated uncertainty. We compared the suitability of presence in all polygons. Figure 2 shows high suitability (30-99%) areas in the ejido polygons. The habitat suitability estimated in each GCM differed. In general, the bighorn sheep habitat availability decreases in the future specially in the extreme RCP 8.5. It is important to notice that climatic suitability in important conservation areas, such as Baja California, ejido Bonfil and Tiburon Island, decreases not only under the less conservative RCP (8.5) but also under RCP 4.6 and 6.9 in almost all GCMs except ESM (Figure 3).

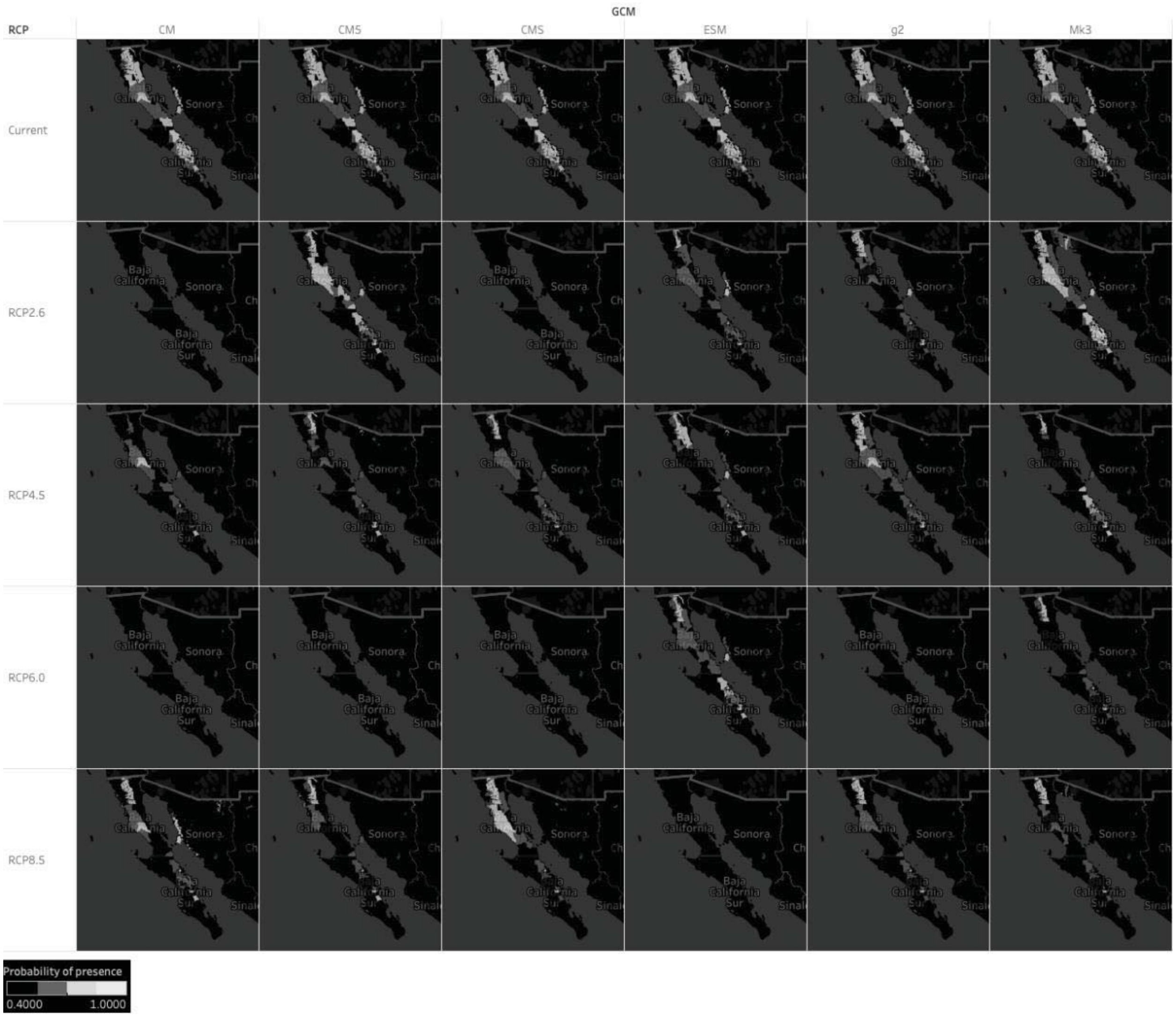


***Figure** 7. Bighorn sheep hábitat suitability in Mexico under current (Chelsa time series 1979-2013) and future (Chelsa time series 2041-2060) bioclimatic conditions.*

For an easy interpretation of changes among GCMs, we developed a GCM consensus map (Figure 4) that incorporates the average values of GCMs. Column three shows the UMA Bonfil polygon changes in habitat suitability. RCP 8.5 is the scenario of emission with major changes in the habitat suitability with respect to current environmental conditions (from 87 to 55%).

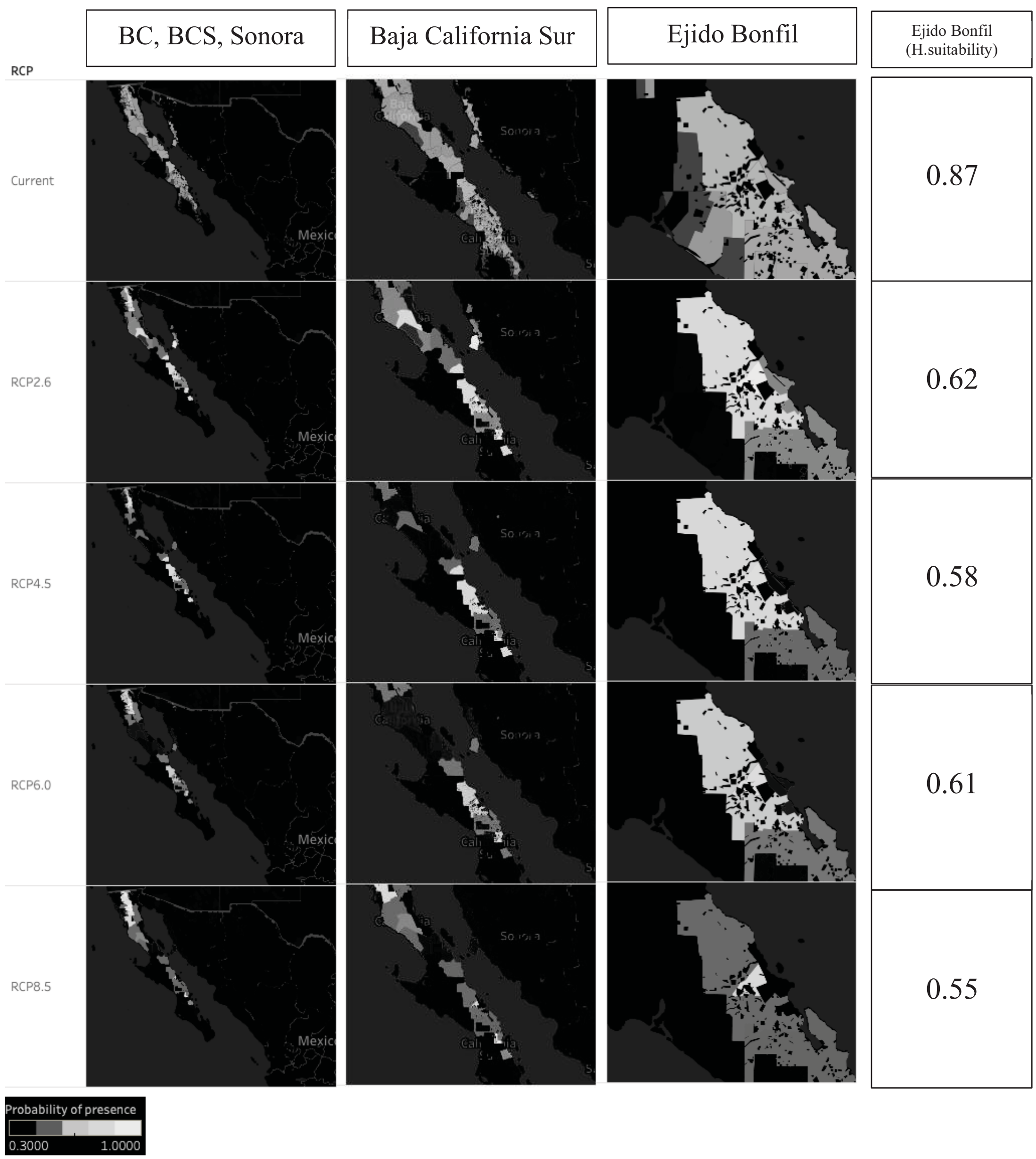


Figure 8. *Bighorn sheep habitat suitability in polygons with high habitat suitabilityunder GCM average values.*

This study found that the suitable area of bighorn sheep changed distinctly in the future projections; climate change scenarios seem to affect the suitable habitat of bighorn sheep. Figure 4, column 2 (Baja California Sur), shows that the habitat suitability in the south polygons in Baja California Sur decreases. However, some polygons in Baja California increase the habitat suitability mainly under the radical RCP 8.5.

Maxent outcomes gives estimates of relative contributions of the environmental variables to the model (Table 4). According to these, Bios (17 and 12) are the most contributed variables in the habitat suitability predictions of *Ovis canadensis* in Mexico.

Table 4. The contribution of bioclimatic variables in the habitat suitability of bighorn sheep in Mexico by ejido

Variable name	**Percent contribution**
Bio17 Precipitation of Driest Quarter	64.3
Bio12 Annual Precipitation	18.6
Bio09 Mean Temperature of Driest Quarter	4.6
Bio11 Mean Temperature of Coldest Quarter	4.3
Bio13 Precipitation of Wettest Month	3.7
Bio08 Mean Temperature of Wettest Quarter	2.5
Bio15 Precipitation Seasonality	2
Bio19 Precipitation of Coldest Quarter	0.1

Therefore, the incidence of precipitation events seems critical for the bighorn sheep, mainly during the three driest months of the year (Table 4, Bio 17). This means that the bighorn sheep is more susceptible to decrease in precipitation, specially under driest periods of the year. Figure 5 also suggests that negative changes the climatic suitability are more drastic at the Sonorense and Baja Californiana ecoregions, where more than half of the ejidos present a negative percentage change with respect to the current suitability, while ejidos in the Californiana ecoregion seems to have a negative percentage change in at least half of its ejidos. Then, the Californiana ecoregion is where ejidos have a lower decrease in the bighorn sheep suitability index (Figure 5).

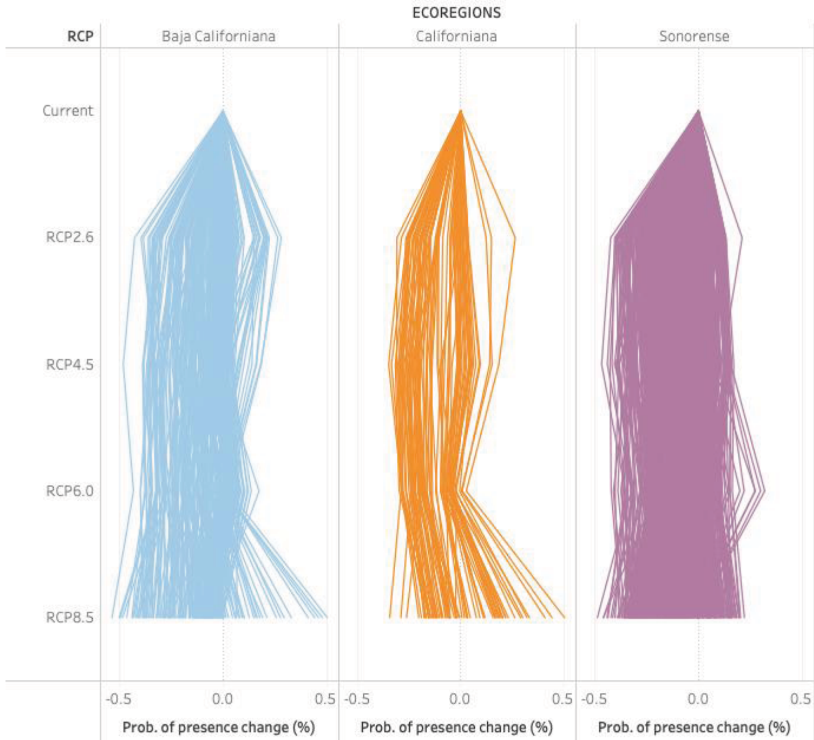


Figure 9. *Bighorn sheep percentage change in the habitat suitability by ecoregion.*

Hence, potential habitat suitability in the future is a multifactorial outcome. In this study we show that GCMs and RCPs are important dimensions in the uncertainty that models face when explore future climate conditions. Then, to get a robust exploration of the possible effects of climate change in the species habitat suitability, it is necessary to integrate all reliable and available data (GCMs, RCPs and species' occurrences). This can lead to a more robust niche model for future habitat suitability analysis with policy-oriented implications.

We can mention some limitations of the model. For instance, it assumes that the estimated index for species' habitat suitability is based on the restrictions imposed by climate variables. However, there are other sources. Such as biological restrictions including predators, disease incidence rates; and anthropogenic restrictions including landscape transformation in to agricultural or urban areas. The present analysis is based on one niche modeling approach (Maxent). However, different approaches for niche modeling could be used to compare outputs. A more robust analysis can be developed by considering climate projections uncertainty and explore the habitat suitability changes under a wider diversity of GCMs, here we explored six. The present analysis can serve as a guiding principle to give us some idea of what the climate conditions might be in the future and how those futures might impact on the bighorn sheep habitat suitability.

4. Discussion

Precipitation and temperature are undoubtedly two important climate variables influencing species distributions(Zhong et al., 2010). For bighorn sheep, bioclimatic variables (Bio17, 12, 9) have a positive contribution towards bighorn sheep probability of occurrence. For instance, extreme temperature can constrain bighorn sheep distribution limits and influence distribution shifts in many ways. On one hand, in arid regions even a slight decrease in moisture content, whether through increased temperature and increased evapotranspiration or through a decrease in precipitation, could have drastic effects on diet quality and therefore demography. According to this study, precipitation in dry conditions, is fundamental for bighorn sheep. (Douglas and Leslie (1983) found that precipitation during gestation account or the largest proportion of variability in lamb survival. Thus, precipitation apparently plays a large role in reproductive success. Nonetheless, bighorn sheep in many ranges make extensive use of springs and water holes, occur close to water during hot summer months (Andrew, 1994), and physiologically depend on ready access to water during summer (Turner & Weaver, 1980).

Results about polygons with high habitat suitability are particularly important for species management. Mapping out the possible future habitats could help managers find ways to prioritize conservation actions in the landscapes they rely on. Knowledge of climate-based habitat suitability may allow managers and decision makers to focus further efforts on locations with the highest probability of success. Understanding which populations are under the most climate related stress could also be critically important in coming decades to anticipate conservation and management actions. Tingstad et al. (2017) compares static and adaptive land purchase strategies for conservation purposes of *Desmognathus organi* (a salamander). Hence, analysts can help decision makers distinguish future conditions in which their plans will perform well from those in which they will perform poorly. This information can help decision makers identify, evaluate, and choose robust strategies that perform well over a wide range of futures. Then, new methods must be considered to face uncertainty of climate change in species conservation and management. For instance, approaches within the broader field of decision science that aims to help people manage difficult decisions under conditions of deep uncertainty (Kalra et al., 2014; R. Lempert, 2015; R. J. Lempert et al., 2003, 2006). This approach runs models on tens to thousands of different sets of assumptions to describe how plans perform in a range of plausible futures.

4.1.Management implications

Climate change may have more complicated or more detrimental effects when competition, predation, and disease affect the desert bighorn sheep. The use of ecological niche modeling has important applications for management actions. For future reintroductions of desert bighorn sheep, managers should consider elevation, steepness and expected precipitation within the mountain range of consideration. The early identification and protection of habitat refugia into which future populations of bighorn sheep could be managed or use as corridors for dispersal, is a management strategy. It can include the acquisition of conservation lands with greater potential to harbor refugia (Dreiss et al., 2022; Graziano et al., 2022; Hilty et al., 2020; Tingstad et al., 2017). Managers may want to consider translocating individuals among areas of occupied habitat or into new habitat, where appropriate (Langridge et al., 2020b; Ramos et al., 2018). Although translocation is a controversial management strategy with inherent disease and genetic risks, bighorn sheep populations have been successfully translocated at Tiburon Island and Carmen Island (Wilder et al., 2014). Those experiences have shown that it is possible to make a significant contribution in the specie conservation and sustainable management.

In conservation biology and wildlife management, proactive management and formulation of conservation status decisions are relevant (Forrest et al., 2012). Particularly, in large mammalian herbivores that are key drivers of ecosystems' dynamics. These animals modify primary production, nutrient cycles, soil properties and fire regimes, which all have an impact on the ecology of other organisms. Most large herbivores require some type of management within their habitats (Danell, 2006). This management plays an important role in species conservation and in local households when managers get important economic contribution by sustainably managing those populations. Hence, assessing the effects of climate change and variability on these populations is essential for the stewardship of ecosystems and biodiversity (Saba et al., 2012a) and for local livelihoods (Lee, 2008). Some studies have assessed the impacts of climate change and variability on resources that support economically important wildlife species (Chidumayo, 2011) especially in fisheries (Islam et al., 2014a; Sumaila et al., 2011a). However, the impacts of climate change on global biodiversity and how biological species may (or may not) adapt are yet to be quantified (Advani, 2014).

We can mention some limitations of the model. For instance, it assumes that the estimated probability for species' habitat suitability is based on the restrictions imposed by climate variables. However, there are other sources. Such as biological restrictions including predators, disease incidence rates; and anthropogenic restrictions including landscape transformation in to agricultural or urban areas. The present analysis is based on one niche modeling approach (Maxent). However, different approaches for niche modeling could be used to compare outputs. A more robust analysis can be developed by considering climate projections uncertainty and explore the habitat suitability changes under a wider diversity of GCMs, here we explored six. The present analysis could be inaccurate in some areas. But it can serve as a guiding principle to at least give us some idea of what the climate conditions might be in the future and how those futures might impact on the bighorn sheep habitat suitability.

This analysis can be extended by considering multiple species, a wider range of climate projections, strategies that employ an array of environmental policy options and potential for learning that ease the reframing and refocusing of goals with which the wildlife community may need to engage in the face of the climate change challenge. A robust exploration of all available data on the extent to which the future habitat of bighorn sheep may contract over a wide range of plausible future climate change; can suggests that compared to a land conservation strategy that focuses on the best estimate future climate, an adaptive land conservation strategy might expand the range of climate futures over which conservation strategies benefit the specie.

5. Conclusions

Estimating how climate change will affect the distribution of bighorn sheep is of vital importance for management purposes, not only in Mexico, but throughout the range of the species (Canada, USA). The development of species' niche models and projections under future climate change is one of the most useful tools to predict changes in species distribution at the global scale (Cheung et al., 2016; Pereira et al., 2010). However, models at local and regional scales are needed to better understand species-climate dynamics. In the context of wildlife management, it could be a great contribution for management planning and conservation. In this study, the niche model captured observations and reflected the expansion and contractions of bighorn sheep habitat according to climate variability (Figure 2). Our results indicated that the habitat suitability projected overall will be reduce under less conservative RCPs by the end of this century, potentially leading to significant ecological and socioeconomic impacts.

Specific guidance related to climate change effects, such as the identification of future habitat suitability, aids in overall conservation planning efforts for managers with limited time and resources. It is also a useful approach to inform about possible management adaptations that can help sustain the economic activities and social benefits derived from the wildlife conservation. It was not possible to get an estimation of costs associated to management and conservation strategies mentioned in this paper because these proyects are financed by different programs, national, international an local programs. By instance, the amount of money already spent for other species' conservation programs such as *Antilocarpa americana peninsularis* in Mexico is anly mentioned by the director program as an expensive one.

Managing climate uncertainty in conservation planning is a topic of increasing interest. Predictions for species' habitat availability in the future can be highly sensitive to climate projections, which are deeply uncertain. At present, many conservation plans do not quantitatively consider model uncertainty (Spencer & Janzen, 2010). In wildlife management decision-making, the representation of key uncertainties in climate projections is essential, i.e. those relating to future GHG emissions, models' ability to simulate the climate response to changing greenhouse gas concentrations and natural climate variability. Our ability to simulate climate change and natural variability is, however, only quantifiable through consideration of the outputs from multiple models of the climate systems, i.e. multiple GCMs. Thus, the consideration of the spread of GCMs is fundamental to all climate change research. The complexity of many techniques to analyze climate change impacts often means a limited set of emission scenarios (RCPs) and GCMs. This leads to a restricted depiction of the climate change signal currently thought of as plausible. When research feeds into policy development, considering the relevance of the change signal to the application as well as representation of key uncertainties are central to the credibility of the projection.

Hence, when current protection strategies on public and private lands are only based on projected climate impacts, they could be inadequate for the conservation of target taxa. Then, the combination of climate projections and niche models may be most useful in directing attention toward locations that may be suitable for conservation under future conditions (Ashcroft, 2010; Ramirez-Villegas et al., 2014) .Predictions of where to locate new reserves, or where to focus landowner incentive programs, become stronger with the use of different future scenarios to suggest robust locations for conservation action. In this case, it is highly likely that climate niche model would be used to identify the landscape of conservation opportunity, and this is likely the strong suit of niche models (Schwartz, 2012).

Despite limitations, this study highlights the importance of integrating analytical tools such as ENM/SDM in the wildlife management agenda to explore climate uncertainty in conservation planning. However, addressing risks for climate change impacts in bighorn sheep populations will require in-depth knowledge of ecological processes (interactions among species, monitoring land use practices and specie's responses to these changes) and cross-scale adaptation policies at a national, regional, and international scale (Canada, USA and Mexico).

6. Acknowledgements

The first author gratefully acknowledges the Program in Sustainability Sciences, UNAM (Posgrado en Ciencias de la Sostenibilidad, Universidad Nacional Autónoma de México).

7. References

Abbot, R., & Hadžikadić, M. (2016). *Complex Adaptive Systems, Systems Thinking, and Agent-Based Modeling*. SpringerLink.

Adger, W. (2000). Social and Ecological resilience, are they related? *Progress in Human Geography*, *24*, 346–364. https://doi.org/10.1191/030913200701540465

Adger, W. N. (2010). Social Capital, Collective Action, and Adaptation to Climate Change 1. *Economic Geography*.

Advani, N. (2014). *Climate Change Vulnerability Assessment for Species*. https://doi.org/10.13140/RG.2.1.3613.5522

Allen, C. R., & Garmestani, A. S. (2015). *Adaptive Management of Social-Ecological Systems.* . SpringerLink.

Allouche, O., Tsoar, A., & Kadmon, R. (2006). Assessing the accuracy of species distribution models: Prevalence, kappa and the true skill statistic (TSS). *Journal of Applied Ecology*, *43*(6), 1223–1232. https://doi.org/10.1111/j.1365-2664.2006.01214.x

Alvarez-Cárdenas, S., Galina-Tessaro, P., Díaz-Castro, S., Guerrero-Cárdenas, I., Castellanos-Vera, A., Mesa-Zavala, E., Investigaciones, C. de, No, S. C. M. B., Palo, P., Rita, D. S., Paz, L., & Sur, B. C. (2009). Evaluación de elementos estructurales del hábitat del borrego cimarrón en la Sierra del Mechudo , Baja California Sur , México. *Tropical Conservation Science*, *2*(2), 189–203.

Andrew, N. (1994). *Demography and Habitat Use of Desert-Dwelling Mountain Sheep in the East Chocolate Mountains, Imperial County, California*. University of Rhode Island.

Armitage, D., Béné, C., Charles, A. T., Johnson, D., & Allison, E. H. (2012). The interplay of well-being and resilience in applying a social- ecological perspective. *Ecology and Society*, *17*(4). https://doi.org/10.5751/ES-04940-170415

Ashcroft, M. B. (2010). Identifying refugia from climate change. *Biogeography*, *37*, 1407–1413.

Avila-Foucat, V. S., & Pérez-Campuzano, E. (2015). Municipality socioeconomic characteristics and the probability of occurrence of Wildlife Management Units in Mexico. *Environmental Science and Policy*, *45*, 146–153. https://doi.org/10.1016/j.envsci.2014.08.005

Bálint, M., Domisch, S., Engelhardt, C. H. M., Haase, P., Lehrian, S., Sauer, J., Theissinger, K., Pauls, S. U., & Nowak, C. (2011). Cryptic biodiversity loss linked to global climate change. *Nature Climate Change*, *1*(6), 313–318. https://doi.org/10.1038/nclimate1191

Bammer, G. (2005). Guiding principles for integration in natural resource management (NRM) as a contribution to sustainability. *Australasian Journal of Environmental Management*, *12*(SUPPL.1), 5–7. https://doi.org/10.1080/14486563.2005.9725099

Biggs, H., Pollard, S., & Toit, D. (2015). SYSTEMIC LINKS BETWEEN SOCIETY , WETLANDS AND WOODLANDS - THE BUSHBUCKRIDGE CASE. *UNPUBLISHED*, *October*, 246–256.

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E. L., BurnSilver, S., Cundill, G., Dakos, V., Daw, T. M., Evans, L. S., Kotschy, K., Leitch, A. M., Meek, C., Quinlan, A., Raudsepp-Hearne, C., Robards, M. D., Schoon, M. L., Schultz, L., & West, P. C. (2012). Toward Principles for Enhancing the Resilience of Ecosystem Services. *Annual Review of Environment and Resources*, *37*(1), 421–448. https://doi.org/10.1146/annurev-environ-051211-123836

Binder, C. R., Hinkel, J., Bots, P. W. G., & Pahl-Wostl, C. (2013). Comparison of frameworks for analyzing social-ecological systems. *Ecology and Society*, *18*(4). https://doi.org/10.5751/ES-05551-180426

Brewer, G. D. (1999). The Challenges of Interdisciplinarity. *Policy Sciences*, *32*(4), 327–337. https://doi.org/10.1023/A:1004706019826

Bryant, B. P., & Lempert, R. J. (2010). Thinking Inside the Box: A Participatory, Computer- Assisted Approach to Scenario Discovery. *Gical Forecasting and Social Change*, *77*(1), 34–39.

Burgos, A., & Velázquez, A. (2019). A Territory Oriented Approach to Operationilize Sustainable Management. *Global Journal of Human Social Science*, *11*.

Carabias, J., Sarukhán, J., de la Maza, J., & Galindo, C. (2010). Patrimonio Natural de México. Cien casos de éxito. In *Patrimonio natural de México. Cien casos de éxito*.

Carpenter, S. R., Arrow, K. J., Barrett, S., Biggs, R., Brock, W. A., Crépin, A. S., Engström, G., Folke, C., Hughes, T. P., Kautsky, N., Li, C. Z., Mccarney, G., Meng, K., Mäler, K. G., Polasky, S., Scheffer, M., Shogren, J., Sterner, T., Vincent, J. R., … de Zeeuw, A. (2012). General resilience to cope with extreme events. *Sustainability*, *4*(12), 3248–3259. https://doi.org/10.3390/su4123248

Carpenter, S. R., Westley, F., & Turner, M. G. (2005). Surrogates for resilience of social-ecological systems. In *Ecosystems* (Vol. 8, Issue 8, pp. 941–944). https://doi.org/10.1007/s10021-005-0170-y

Carpenter, S., Walker, B., Anderies, J. M., & Abel, N. (2001). From Metaphor to Measurement: Resilience of What to What? *Ecosystems*, *4*(8), 765–781. https://doi.org/10.1007/s10021-001-0045-9

Carpenter, Stephen., & Gunderson, Lance. (2001). Coping with Collapse: Ecological and Social Dynamics in Ecosystem Management. *BioScience*, *51*(6), 451. https://doi.org/10.1641/0006-3568(2001)051[0451:CWCEAS]2.0.CO;2

Ceballos, G., & Oliva, G. (2005). *Los mamíferos silvestres de México.* CONABIO—Fondo de Cultura Económica.

Cheung, W., Jones, M., & Lam, V. (2016). Transform high seas management to build climate resilience in marine seafood supply. *Fish and Fisheries*.

Chidumayo, Emmanuel. (2011). *Climate change and african forest and wildlife resources*. African Forest Forum.

Cilliers, P., Biggs, H. C., Blignaut, S., Choles, A. G., Jewitt, G. P. W., & Roux, D. J. (2013). Complexity , Modeling , and Natural Resource Management. *Ecology and Society*, *18*(3).

Colchero, F., Medellin, R. A., Clark, J. S., Lee, R., & Katul, G. G. (2009). Predicting population survival under future climate change: Density dependence, drought and extraction in an insular bighorn sheep. *Journal of Animal Ecology*, *78*(3), 666–673. https://doi.org/10.1111/j.1365-2656.2009.01528.x

Conagua. (2012). *Atlas del agua en México 2012*. https://doi.org/ISBN: 978-607-8246-29-8

Contreras, A., & Espinosa, A. (2010). Evaluación de hábitat para la restauración del borrego cimarrón (Ovis canadensis) en Coahuila, México. *Redalyc*, *13*(1), 78–86.

Cumming, G. S., Barnes, G., Perz, S., Schmink, M., Sieving, K. E., Southworth, J., Binford, M., Holt, R. D., Stickler, C., & van Holt, T. (2005). An exploratory framework for the empirical measurement of resilience. *Ecosystems*, *8*(8), 975–987. https://doi.org/10.1007/s10021-005-0129-z

Cumming, G. S., & Peterson, G. D. (2017). Unifying Research on Social–Ecological Resilience and Collapse. In *Trends in Ecology and Evolution* (Vol. 32, Issue 9). https://doi.org/10.1016/j.tree.2017.06.014

D'Almeida Martins, R., & da Costa Ferreira, L. (2011). Opportunities and constraints for local and subnational climate change policy in urban areas: Insights from diverse contexts. *International Journal of Global Environmental Issues*, *11*(1), 37–53. https://doi.org/10.1504/IJGENVI.2011.040250

Danell, Kjell. (2006). *Large herbivore ecology, ecosystem dynamics and conservation*. Cambridge University Press.

Daw, Coulthard, Cheung, Brown, K., Abunge, C., Galafassi, D., Peterson, G., McClanahan, T., Omukoto, O., & Munyi, L. (2015). Evaluating taboo trade-offs in ecosystems services and human well-being. *PNAS*.

DeCesare, N., & Pletscher, D. H. (2006). Movements, Connectivity, and Resource Selection of Rocky Mountain Bighorn Sheep. *Journal of Mammalogy*, *87*(3), 531–538. https://doi.org/10.1644/05-MAMM-A-259R1.1

Ding, H., & Nunes, P. (2014). Modeling the links between biodiversity , ecosystem services and human wellbeing in the context of climate change : Results from an econometric analysis of the European forest ecosystems. *Ecological Economics*, *97*, 60–73. https://doi.org/10.1016/j.ecolecon.2013.11.004

Douglas, C. L., & Leslie, D. M. (1983). Influence of Weather and Density on Lamb Survival of Desert Mountain Sheep. *He Journal of Wildlife Management* , *50*, 153–156.

Dreiss, L. M., Hessenauer, J. M., Nathan, L. R., O'Connor, K. M., Liberati, M. R., Kloster, D. P., Barclay, J. R., Vokoun, J. C., & Morzillo, A. T. (2017). Adaptive Management as an Effective Strategy: Interdisciplinary Perceptions for Natural Resources Management. *Environmental Management*, *59*(2), 218–229. https://doi.org/10.1007/s00267-016-0785-0

Dreiss, L. M., Lacey, L. M., Weber, T. C., Delach, A., Niederman, T. E., & Malcom, J. W. (2022). Targeting current species ranges and carbon stocks fails to conserve biodiversity in a changing climate: Opportunities to support climate adaptation under 30 × 30. *Environmental Research Letters*, *17*(2). https://doi.org/10.1088/1748-9326/ac4f8c

Duncan, D. H., & Wintle, B. A. (2008). Towards Adaptive Management of Native Vegetation in Regional Landscapes. In C. W. Pettit C., Bishop I., Lowell K., Pullar D., & Duncan D. (Eds.), *Landscape Analysis and Visualisation. Lecture Notes in Geoinformation and Cartography.* (pp. 160–181). https://doi.org/https://doi.org/10.1007/978-3-540-69168-6_9

Escobar-Flores, J. G., Alvarez-Cardenas, S., Valdez, R., Torres-Rodriguez, J., Díaz-Castro, S., Castellanos-Vera, A., & Martinez-Gallardo, R. (2015). Detección de las preferencias de hábitat del borrego cimarrón (Ovis canadensis cremnobates) en Baja

California, mediante Técnicas de Teledetección Satelital. *Therya*, *6*(3), 519–534. https://doi.org/10.12933/therya-15-284
Fischbach, J. R., Johnson, D. R., & Groves, D. G. (2019). Flood damage reduction benefits and costs in Louisiana's 2017 coastal master plan. . *Environ. Res. Commun*.
Fischer, J., Gardner, T. A., Bennett, E. M., Balvanera, P., Biggs, R., Carpenter, S., Daw, T., Folke, C., Hill, R., Hughes, T. P., Luthe, T., Maass, M., Meacham, M., Norström, A. v., Peterson, G., Queiroz, C., Seppelt, R., Spierenburg, M., & Tenhunen, J. (2015). Advancing sustainability through mainstreaming a social-ecological systems perspective. *Current Opinion in Environmental Sustainability*, *14*, 144–149. https://doi.org/10.1016/j.cosust.2015.06.002
Folke, C. (2006). Resilience: The emergence of a perspective for social-ecological systems analyses. *Global Environmental Change*, *16*(3), 253–267. https://doi.org/10.1016/j.gloenvcha.2006.04.002
Folke, C., Biggs, R., Norström, A. v., Reyers, B., & Rockström, J. (2016). Social-ecological resilience and biosphere-based sustainability science. *Ecology and Society*, *21*(3). https://doi.org/10.5751/ES-08748-210341
Folke, C., Carpenter, S., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2010). Resilience Thinking : Integrating Resilience , Adaptability and Transformability. *Ecology and Society*, *15*(4), 20.
Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., & Holling, C. S. (2004). Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology, Evolution, and Systematics*, *35*, 557–581. https://doi.org/10.1146/annurev.ecolsys.35.021103.105711
Folke, C., Jansson, Å., Rockström, J., Olsson, P., Carpenter, S. R., Stuart Chapin, F., Crépin, A. S., Daily, G., Danell, K., Ebbesson, J., Elmqvist, T., Galaz, V., Moberg, F., Nilsson, M., Österblom, H., Ostrom, E., Persson, Å., Peterson, G., Polasky, S., … Westley, F. (2011). Reconnecting to the biosphere. *Ambio*, *40*(7), 719–738. https://doi.org/10.1007/s13280-011-0184-y
Forrest, J. L., Wikramanayake, E., Shrestha, R., Areendran, G., Gyeltshen, K., Maheshwari, A., Mazumdar, S., Naidoo, R., Thapa, G. J., & Thapa, K. (2012). Conservation and climate change: Assessing the vulnerability of snow leopard habitat to treeline shift in the Himalaya. *Biological Conservation*, *150*(1), 129–135. https://doi.org/10.1016/j.biocon.2012.03.001
Forrester, J. W. (1994). System dynamics, systems thinking, and soft OR. *System Dynamics Review*, *10*(2).
Galvani, A. P., Bauch, C. T., Anand, M., Singer, B. H., & Levin, S. A. (2016). Human-environment interactions in population and ecosystem health. In *Proceedings of the National Academy of Sciences of the United States of America* (Vol. 113, Issue 51, pp. 14502–14506). National Academy of Sciences. https://doi.org/10.1073/pnas.1618138113
García, J. T., Jiménez, J., Mateo, R., & Arroyo, B. (2016). *Current Trends in Wildlife Research*. *1*, 283–293. https://doi.org/10.1007/978-3-319-27912-1
Garcia, R. A., Cabeza, M., Rahbek, C., & Araújo, M. B. (2014). Multiple dimensions of climate change and their implications for biodiversity. In *Science* (Vol. 344, Issue 6183). American Association for the Advancement of Science. https://doi.org/10.1126/science.1247579

Gedir, J. v, Cain, J. W., Swetnam, T. L., Krausman, P. R., & Morgart, J. R. (2020). Extreme drought and adaptive resource selection by a desert mammal. *Ecosphere*, *11*(17). https://doi.org/doi:e03175. 10.1002/ecs2.3175

González-Saldívar, F., Tarango-Arámbula, L. a, Cantú-Ayala, C., Uvalle-Sauceda, J., Marmolejo-Moncivais, J., & Ríos-Saldaña, C. (2012). Estudio Poblacional y de distribución del borrego cimarrón (Ovis canadensis mexicana , merriam , 1901) en Sonora. *Revista Mexicana de Ciencias Forestales*, *2*(4), 63–75.

Graziano, M. P., Deguire, A. K., & Surasinghe, T. D. (2022). Riparian Buffers as a Critical Landscape Feature: Insights for Riverscape Conservation and Policy Renovations. In *Diversity* (Vol. 14, Issue 3). MDPI. https://doi.org/10.3390/d14030172

Grinnell, J. (1917). The Niche-Relationships of the California Thrasher. *The Auk JSTOR*, *34*(4), 427–433.

Groves, D. G., Bonzanigo, L., Syme, J., Engle, N. L., & Rodriguez Cabanillas, I. (2019). *Preparing for Future Droughts in Lima, Peru: Enhancing Lima's Drought Management Plan to Meet Future Challenges. Washington, DC: World Bank*.

Groves, D. G., Kuhn, K., Fischbach, J. R., Johnson, D. R., & Syme, J. (2016). *Analysis to Support Louisiana's Flood Risk and Resilience Program and Application to the National Disaster Resilience Competition*.

Groves, D. G., & Lempert, R. J. (2007). A new analytic method for finding policy-relevant scenarios. *Global Environ. Change*, *17*, 73–85.

Guerrero-Cárdenas, I., Tovar-Zamora, I., & Álvarez-Cárdenas, S. (2003). Factores que afectan la distribución espacial del borrego cimarrón Ovis canadensis weemsi en la Sierra del Mechudo ,. *Anales Del Instituto de Biología, Universidad Nacional Autónoma de México, Serie Zoología*, *74*(195), 83–98.

Guerry, A. D., Polasky, S., Lubchenco, J., Chaplin-Kramer, R., Daily, G. C., Griffin, R., Ruckelshaus, M., Bateman, I. J., Duraiappah, A., Elmqvist, T., Feldman, M. W., Folke, C., Hoekstra, J., Kareiva, P. M., Keeler, B. L., Li, S., McKenzie, E., Ouyang, Z., Reyers, B., … Vira, B. (2015). Natural capital and ecosystem services informing decisions: From promise to practice. In *Proceedings of the National Academy of Sciences of the United States of America* (Vol. 112, Issue 24, pp. 7348–7355). National Academy of Sciences. https://doi.org/10.1073/pnas.1503751112

Guisan, A., Tingley, R., Baumgartner, J. B., Naujokaitis-Lewis, I., Sutcliffe, P. R., Tulloch, A. I. T., Regan, T. J., Brotons, L., Mcdonald-Madden, E., Mantyka-Pringle, C., Martin, T. G., Rhodes, J. R., Maggini, R., Setterfield, S. A., Elith, J., Schwartz, M. W., Wintle, B. A., Broennimann, O., Austin, M., … Buckley, Y. M. (2013). Predicting species distributions for conservation decisions. *Ecology Letters*, *16*(12), 1424–1435. https://doi.org/10.1111/ele.12189

Gunderson, L. H., & Holling, C. S. (2002). *Panarchy:Undestanding Transformations in Human and Natural Systems* (L. H. Gunderson & C. S. Holling, Eds.). Island Press.

Head, B. W., & Alford, J. (2015). Wicked Problems: Implications for Public Policy and Management. *Administration and Society*, *47*(6), 711–739. https://doi.org/10.1177/0095399713481601

Heffelfinger, J. R., & Marquez-Muñoz, E. (2005). Historical occurrence and distribution of desert bighorn sheep in Chihuahua , Mexico. *DESERT BIGHORN COUNCIL TRANSACTIONS*, *48*, 28–38.

Helena, C. (2020). *Translocación y reintroducción como estrategias complementarias para la conservación del endémico y críticamente amenazado Paujil de pico azul (Crax alberti)*.

Hilty, J., Worboys, G. L., Keeley, A., Woodley, S., Lausche, B., Locke, H., Carr, M., Pulsford, I., Pittock, J., White, J. W., Theobald, D. M., Levine, J., Reuling, M., Watson, J. E. M., Ament, R., & Tabor, G. M. (2020). *Guidelines for conserving connectivity through ecological networks and corridors Best Practice Protected Area Guidelines Series No. 30 Developing capacity for a protected planet*. www.iucn.org/pa_guidelines

Hirzel, A. H., Lay L., Helfer, V., Randin, C., & Guisan, A. (2006). Evaluating the ability of habitat suitability models to predict species presences.(2006): 142-152. *Ecological Modelling*, 142–152.

Hoegh-Guldberg, O., Kenned, E., Beyer, H., McClennen, C., & Possingham, H. (2018). Securing a Long-term Future for Coral Reefs. *Trends in Ecology & Evolution*, *33*(12), 936–944.

Holling, C. S. (2001). Understanding Complexity of Economic, Ecological, and Social Systems. *Ecosystems*, *4*, 390–405.

Huerta-García, A., Ramírez-Milanés, M. N., Valenzuela-Núñez, L. M., & Abad-Zavaleta, J. (2015). Aprovechamiento del borrego cimarrón (Ovis canadensis mexicana) en unidades de manejo del noreste de México. *Ecosistemas y Recursos Agropecuarios*, *2*(6), 339–347.

Hughes, T. P., Carpenter, S., Rockström, J., Scheffer, M., & Walker, B. (2013). Multiscale regime shifts and planetary boundaries. *Trends in Ecology and Evolution*, *28*(7), 389–395. https://doi.org/10.1016/j.tree.2013.05.019

Hull, V., Tuanmu, M.-N., & Liu, J. (2015). Ecology and Society: Synthesis of human-nature feedbacks. *Ecology and Society*, *20*(3), 17. http://www.ecologyandsociety.org/vol20/iss3/art17/

IPCC. (2021a). *IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou, Eds.). Cambridge University Press.

IPCC. (2021b). Technical Summary. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In *Climate Change 2021: The Physical Science Basis.*

Islam, M. M., Sallu, S., Hubacek, K., & Paavola, J. (2014a). Vulnerability of fishery-based livelihoods to the impacts of climate variability and change: Insights from coastal Bangladesh. *Regional Environmental Change*, *14*(1), 281–294. https://doi.org/10.1007/s10113-013-0487-6

Islam, M. M., Sallu, S., Hubacek, K., & Paavola, J. (2014b). Vulnerability of fishery-based livelihoods to the impacts of climate variability and change: Insights from coastal Bangladesh. *Regional Environmental Change*, *14*(1), 281–294. https://doi.org/10.1007/s10113-013-0487-6

Isley, S. C., Lempert, R. J., Popper, S. W., & Vardavas, R. (2015). The effect of near-term policy choices on long-term greenhouse gas transformation pathways. *Glob. Environ. Change*, *34*, 147–158.

Kalra, N., Hallegatte, S., Lempert, R., Brown, C., Fozzard, A., Gill, S., & Shah, A. (2014). *Agreeing on Robust Decisions New Processes for Decision Making Under Deep Uncertainty*. http://econ.worldbank.org.

Karger, D. N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R. W., Zimmermann, N. E., Linder, H. P., & Kessler, M. (2018). *Data from: Climatologies at high resolution for the earth's land surface areas*. https://doi.org/10.5061/dryad.kd1d4

Kasprzyk, J. R., Nataraj, S., Reed, P. M., & Lempert, R. J. (2013). Many objective robust decision making for complex environmental systems undergoing change. *Environ. Model. Softw.*, *42*, 55–71.

Kates. (2001). Sustainability Science. *Science*, *292*(5517), 641–642. https://doi.org/10.1126/science.1059386

Kengar, A., Vinayake, K., Mallia, J., Darade. M, Kumar, B., & Chahande, S. (2021). *Ecology Research* (A. Kengar, M. Darade, K. Vinayake, B. Kumar, J. Mallia, & S. Chahande, Eds.; Vol. 2).

Köberle, A. C., Vandyck, T., Guivarch, C., Macaluso, N., Bosetti, V., Gambhir, A., Tavoni, M., & Rogelj, J. (2021). The cost of mitigation revisited. In *Nature Climate Change*. Nature Research. https://doi.org/10.1038/s41558-021-01203-6

Kwakkel, J. H. (2017). The exploratory modeling workbench: an open source toolkit for exploratory modeling, scenario discovery, and (multiobjective) robust decision making. . *Environ. Model. Softw.* , *96*, 239–250.

Langridge, J., Sordello, R., & Reyjol, Y. (2020a). Outcomes of wildlife translocations in protected areas: what is the type and extent of existing evidence? A systematic map protocol. *Environmental Evidence*, *9*(1). https://doi.org/10.1186/s13750-020-00199-4

Langridge, J., Sordello, R., & Reyjol, Y. (2020b). Outcomes of wildlife translocations in protected areas: what is the type and extent of existing evidence? A systematic map protocol. *Environmental Evidence*, *9*(1). https://doi.org/10.1186/s13750-020-00199-4

Langridge, J., Sordello, R., & Reyjol, Y. (2021). Existing evidence on the outcomes of wildlife translocations in protected areas: a systematic map. *Environmental Evidence*, *10*(1). https://doi.org/10.1186/s13750-021-00236-w

Larson, A. M., & Ribot, J. C. (2007). The poverty of forestry policy: Double standards on an uneven playing field. *Sustainability Science*, *2*(2), 189–204. https://doi.org/10.1007/s11625-007-0030-0

Lee, R. (2003). A review of recent wild sheep surveys in Baja California Sur, Mexico. *Desert Bighorn Council Transaction*, *43*, 43–46.

Lee, R. (2008). Hunting as a Tool For Wildlife Conservation: The Case of Sheep Hunting in Mexico. In R. D. Baldus, G. R. Damm, & K. Wollscheid (Eds.), *Best Practices in Sustainable Hunting A Guide to Best Practices From Around the World*.

Lee, R. (2016). *Monitoreo Aéreo de la Población de Borrego Cimarron en Baja California Sur (2016). Reporte Técnico No Publicado*.

Lempert, R. (2015). Selection of climate policies under the uncertainties in the Fifth Assessment Report of the IPCC. *Nature Climate Change*, *5*(10), 937–943. https://doi.org/10.1038/nclimate2721

Lempert, R. J., & Groves, D. G. (2010). Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west. *Technol. Forecast. Soc. Change*, *77*, 960-974.

Lempert, R. J., Groves, D. G., Popper, S., & Bankes, S. C. (2006). A general, analytic method for generating robust strategies and narrative scenarios. *Manag. Sci.*, *52*, 514–528.

Lempert, R. J., Popper, S. W., & Bankes, S. C. (2003). *Shaping the next one hundred years : new methods for quantitative, long-term policy analysis and bibliography*. RAND.

Levin, S. (1998). The Ecosystems and Biosphere Complex Adaptive Systems. *Ecosystems*, 431–436.

Levin, S., Xepapadeas, T., Crépin, A.-S., Norberg, J., de Zeeuw, A., Folke, C., Hughes, T., Arrow, K., Barrett, S., Daily, G., Ehrlich, P., Kautsky, N., Mäler, K.-G., Polasky, S., Troell, M., Vincent, J. R., & Walker, B. (2013). Social-ecological systems as complex adaptive systems: modeling and policy implications. *Environment and Development Economics*, *18*(02), 111–132. https://doi.org/10.1017/S1355770X12000460

Lindig, R., Galindo, S., & Lara, S. (2006). Historical distribution of desert bighorn sheep (ovis canadensis mexicana) in Coahuila Mexico. *The Southwestern Naturalist*, *51*(4), 455–461. https://doi.org/10.1894/0038-4909(2006)51

Liu, J., Hull, V., Batistella, M., DeFries, R., Dietz, T., Fu, F., Hertel, T. W., Izaurralde, R. C., Lambin, E. F., Li, S., Martinelli, L. A., McConnell, W. J., Moran, E. F., Naylor, R., Ouyang, Z., Polenske, K. R., Reenberg, A., Rocha, G. de M., Simmons, C. S., … Zhu, C. (2013). Framing Sustainability in Telecoupled World. *Ecology and Society 18(2):*, *18*(12), 26. https://doi.org/. http://dx.doi.org/10.5751/ ES-05873-180226 Synthesis

López-Feldman, A., & Wilen, J. E. (2008). Poverty and spatial dimensions of non-timber forest extraction. *Environment and Development Economics*, *13*(05), 1–43. https://doi.org/10.1017/S1355770X08004518

Lynam, T., de Jong, W., Sheil, D., Kusumanto, T., & Evans, K. (2007). A review of tools for incorporating community knowledge, preferences, and values into decision making in natural resources management. *Ecology and Society* , *12*(1).

Maida, C. A., & Beck, S. (2018). *Global Sustainability and Communities of Practice* (1st ed.). Berghahn Books JSTOR.

Manterola, C. (2001). *Censo aéreo de poblaciones de borrego cimarrón (Ovis canadensis cremnobates) en Baja California , México*.

Manterola y Piña, C. (1999). Monitoreo de las poblaciones de borrego cimarrón (Ovis canadensis weemsi) en Baja California Sur, México. In *SNIB-CONABIO*.

Marchau, V. A. W. J., Walker, W. E., Bloemen, M., P. J. T., & Popper, S. W. (2019). Decision Making Under Deep Uncertainty. In V. A. W. J. Marchau, W. E. Walker, P. J. T. Bloemen, M., & S. W. Popper (Eds.), *The Oxford Handbook of Planning for Climate Change Hazards*. https://doi.org/10.1093/oxfordhb/9780190455811.013.50

Marchau, V., Walker, W. E., A.Bloemen, P. J., & Popper, S. W. (2019). *Decision Making under Deep Uncertainty*. Springer International Publishing. https://doi.org/10.1007/978-3-030-05252-2

Mayer, I. S., van Daalen, C. E., & Bots, P. W. G. (2004). Perspectives on policy analyses: A framework for understanding and design. In *International Journal of Technology, Policy and Management* (Vol. 4, Issue 2, pp. 169–191). Inderscience Publishers. https://doi.org/10.1504/IJTPM.2004.004819

Mckinney, T., Smith, T., & DeVos, J. (2003). Evaluation of Factors Potentially Influencing a Desert Bighorn Sheep Population. *The Wildlife Society*, *0173*, 1–36.

Medeiros, E. (2016). Is there a rise of the territorial dimension in the EU Cohesion Policy ? *Finisterra*.

Meltzer, R., & Schwartz, A. (2019). *Policy Analysis as Problem Solving: A Flexible and Evidence-Based Framework*. Routledge.

Mesa, E. (2013). *Diagnóstico del hábitat del borrego cimarrón en funcion de variables ambientales y actividades antropogénicas en la sierra El Mechudo Baja California Sur, México.* Centro de Investigaciones Biológicas del Noreste, S. C.

Milner-Gulland, E. J. (2012). Interactions between human behaviour and ecological systems. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*(1586), 270–278. https://doi.org/10.1098/rstb.2011.0175

Molina-Perez, E., Esquivel-Flores, O. A., & Zamora-Maldonado, H. (2020). Computational Intelligence for Studying Sustainability Challenges: Tools and Methods for Dealing With Deep Uncertainty and Complexity. *Frontiers in Robotics and AI*, *7*. https://doi.org/10.3389/frobt.2020.00111

Molina-Perez, E., Groves, D. G., Popper, S. W., Ramirez, A. I., & Crespo-Elizondo, R. (2019). *Developing a robust water strategy for Monterrey, Mexico : diversification and adaptation for coping with climate, economic, and technological uncertainties*.

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H., & Schwarz, N. (2013). Describing human decisions in agent-based models - ODD+D, an extension of the ODD protocol. *Environmental Modelling and Software*, *48*, 37–48. https://doi.org/10.1016/j.envsoft.2013.06.003

Murray, C., & Marmorek, D. (2003). Adaptive Management and Ecological Restoration. In P. Freiderici (Ed.), *Ecological Restoration of Southwestern Ponderosa Pine Forests* (pp. 417–428). Island Press.

Nelson, D. R., Adger, W. N., & Brown, K. (2007). Adaptation to Environmental Change: Contributions of a Resilience Framework. *Annual Review of Environment and Resources*, *32*(1), 395–419. https://doi.org/10.1146/annurev.energy.32.051807.090348

O´Farril, E. (2003). *Dieta y uso del hábitat del borrego cimarrón (Ovis canadensis mexicana) y el venado bura (Odocoileus hemionus sheldoni) en Isla Tiburón, Sonora, México*. Universidad Nacional Autónoma de México.

O'Higgins, T. G., Lago, M., & DeWitt, T. H. (2020). *Ecosystem-Based Management, Ecosystem Services and Aquatic Biodiversity* (T. G. O'Higgins, M. Lago, & T. H. DeWitt, Eds.). Springer. https://doi.org/https://doi.org/10.1007/978-3-030-45843-0

Oliver, K., & Cairney, P. (2019). The dos and don'ts of influencing policy: a systematic review of advice to academics. In *Palgrave Communications* (Vol. 5, Issue 1). Palgrave Macmillan Ltd. https://doi.org/10.1057/s41599-019-0232-y

Ordoñez-Matamoros. (2013). *Manual de Análisis y Diseño de Políticas Públicas*. Panamericana.

Ostrom, E. (2005). *Understanding Institutional Diversity*. Princeton University Press.

Ostrom, E. (2009). A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science*, *325*, 419–423.

Owen, G. (2020). What makes climate change adaptation effective? A systematic review of the literature. *Global Environmental Change*, *62*. https://doi.org/10.1016/j.gloenvcha.2020.102071

Palomo-Ramos, R., Ramos, P., Colima, G., & Arana, R. (n.d.). *REVISTA BIO CIENCIAS Translocation as a conservation tool for endangered tortoises in Mexico Las translocaciones como herramienta de conservación para las tortugas terrestres en México*. https://doi.org/10.15741/revbio.05.01.01

Parker, J., Simpson, G. D., & Miller, J. E. (2020). Nature-based solutions forming urban intervention approaches to anthropogenic climate change: A quantitative literature review. In *Sustainability (Switzerland)* (Vol. 12, Issue 18). MDPI. https://doi.org/10.3390/SU12187439

Pereira, H., Leadleyvania, P., & Proença, V. (2010). Scenarios for Global Biodiversity in the 21st Century. *Science*, *330*(6010).

Perry, D. C., Chaffee, C., Wigand, C., & Thornber, C. (2020). Implementing adaptive management into a climate change adaptation strategy for a drowning New England salt marsh. *Journal of Environmental Management*, *270*. https://doi.org/10.1016/j.jenvman.2020.110928

Peterson, T., & Anamza, T. (2015). Ecological niches and present and historical geographic distributions of species: a 15-year review of frameworks, results, pitfalls, and promises. *Folia Zoologica*, *64*(3), 207–217.

Phillips, S. J., Anderson, R. P., Dudík, M., Schapire, R. E., & Blair, M. E. (2017). Opening the black box: an open-source release of Maxent. *Ecography*, *40*(7), 887–893. https://doi.org/10.1111/ecog.03049

Phillips, S. J., & Dudík, M. (2008). *Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation*. https://doi.org/10.1111/j.2007.0906-7590.05203.x

Pires, A. P. F., Srivastava, D. S., Marino, N. A. C., Andrew, A., Macdonald, M., Figueiredo-Barros, M. P., & Farjalla, V. F. (2018). *Interactive effects of climate change and biodiversity loss on ecosystem functioning*.

Popper, S. W., Berrebi, C., Griffin, J., Crane, K., Light, T., & Daehner, E. M. (2009). *Natural Gas and Israel's Energy Future*.

Ramirez-Villegas, J., Devenish, F., & Cuesta, F. (2014). Using species distributions models for designing conservation strategies of Tropical Andean biodiversity under climate change. *Nature Conservation*, *22*(5), 391–404.

Ramos, P., Colima, G., & Arana, R. (2018). Translocation as a conservation tool for endangered tortoises in Mexico. *REVISTA BIO CIENCIAS* . https://doi.org/10.15741/revbio.05.01.01

Resilience Alliance. (2015). ASSESSING RESILIENCE IN SOCIAL-ECOLOGICAL SYSTEMS. *Stockholm University*, *June*, 1–53. http://www.stockholmresilience.org/21/research/what-is-resilience/research-background/research-framework/social-ecological-systems.html

Robinson, J. G., & Bennett, E. (2001). *Hunting for Sustainability in Tropical Forests* (J. G. Robinson & E. Bennett, Eds.; Vol. 39). Columbia University Press,.

Rodríguez-Ríos, E., & García-Páez, B. (2017). Valuing bushmeat for people living at a subsistence level: The case of *Cuniculus paca* meat in Flavio Alfaro, Manabí, Ecuador. *Human Dimensions of Wildlife*. https://doi.org/10.1080/10871209.2018.1419517

Román, R. (2012). *Densidad y estructura poblacional del Borrego Cimarrón (Ovis canadensis weemsi, Goldman, 1937) en la Isla "El Carmen", Baja California Sur, México*. Universidad Autónoma de Nuevo León.

Ruíz, E. (2014). *Estado actual de la población de borrego cimarrón (Ovis canadensis weemsi) En la UMA ejido La Purísima, Baja California Sur, México*. Universidad Nacional Autónoma de México.

Saavedra, E., Lee, R. M., de Vos, J. C., Schweinsburg, R. E., & Salazar, G. (1999). Relación Uso-Disponibilidad De Componentes Topográficos Y Un Modelo De Calidad Del Hábitat Para El Borrego Cimarrón, En Sonora, México. *Acta Zoológica Mexicana (Ns)*, *76*, 17–34.

Saba, V. S., Stock, C. A., Spotila, J. R., Paladino, F. v., & Tomillo, P. S. (2012a). Projected response of an endangered marine turtle population to climate change. *Nature Climate Change*, *2*(11), 814–820. https://doi.org/10.1038/nclimate1582

Saba, V. S., Stock, C. A., Spotila, J. R., Paladino, F. v., & Tomillo, P. S. (2012b). Projected response of an endangered marine turtle population to climate change. *Nature Climate Change*, *2*(11), 814–820. https://doi.org/10.1038/nclimate1582

SAGARHPA. (2012). Borrego cimarrón (Ovis canadensis mexicana): Resultados del monitoreo aéreo en el Estado de Sonora, México. Noviembre, 2012. In *SAGARHPA*. http://www.hunting.sonora.gob.mx/convenios/libro.pdf

Scarlett, L. (2013). Collaborative adaptive management: Challenges and opportunities. *Ecology and Society*, *18*(3). https://doi.org/10.5751/ES-05762-180326

Scheffer, M., & Carpenter, S. R. (2003). Catastrophic regime shifts in ecosystems: Linking theory to observation. *Trends in Ecology and Evolution*, *18*(12), 648–656. https://doi.org/10.1016/j.tree.2003.09.002

Schlüter, M., Müller, B., & Frank, K. (2019). The potential of models and modeling for social-ecological systems research: The reference frame ModSES. *Ecology and Society*, *24*(1). https://doi.org/10.5751/ES-10716-240131

Schlüter, M., Orach, K., Lindkvist, E., Martin, R., Wijermans, N., Bodin, Ö., & Boonstra, W. J. (2019). Toward a methodology for explaining and theorizing about social-ecological phenomena. *Current Opinion in Environmental Sustainability*, *39*, 44–53. https://doi.org/10.1016/j.cosust.2019.06.011

Schoenecker, K. A. (2004). Bighorn Sheep Habitat Studies , Population Dynamics , and Population Modeling in Bighorn Canyon National Recreation Area , 2000 – 2003. *Recreation*, 216.

Schwartz, M. (2012). Using niche models with climate projections to inform conservation management decisions. *Biological Conservation*, *155*, 149–156.

SEMARNAT. (2012). Estrategia Estatal Para la Conservación y Manejo Sustentable del Borrego Cimarrón (Ovis canadensis cremnobates) en Baja California. *SEMARNAT*, 91.

Seppelt, R., Müller, F., Schröder, B., & Volk, M. (2009). Challenges of simulating complex environmental systems at the landscape scale: a controversial dialogue between two cups of espresso . *Ecological Modeling*, *220*, 3481–3489.

Spencer, R., & Janzen, F. (2010). Demographic consequences of adaptive growth and the ramifications for conservation of long-lived organisms. *Biological Conservation*, *143*(9), 1951–1959.

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

Sumaila, U. R., Cheung, W. W. L., Lam, V. W. Y., Pauly, D., & Herrick, S. (2011a). Climate change impacts on the biophysics and economics of world fisheries. In *Nature Climate Change* (Vol. 1, Issue 9, pp. 449–456). https://doi.org/10.1038/nclimate1301

Sumaila, U. R., Cheung, W. W. L., Lam, V. W. Y., Pauly, D., & Herrick, S. (2011b). Climate change impacts on the biophysics and economics of world fisheries. In *Nature Climate Change* (Vol. 1, Issue 9, pp. 449–456). https://doi.org/10.1038/nclimate1301

Tarango, L. a., Krausman, P. R., Valdez, R., & Kattnig, R. M. (2006). Research observation: desert bighorn sheep diets in northwestern Sonora, Mexico. *Journal of Range Management Archives*, *55*(6), 530–534. https://doi.org/10.2307/4003995

Tingstad, A. H., Lempert, R. J., Moskwik, M., Warren, D. L., Parmesan, C., Mcginnis, S., & Ryu, Y. (2017). Demonstrating the Applicability of a Robust Decision Making (RDM) to Conservation Decision-Making Under Uncertain Future Climate: Pilot Study Using the Northern Pygmy Salamander (Desmognathus organi). In *Journal of Conservation Planning* (Vol. 13).

Turner, J. C., & Weaver, A. (1980). Water. In G. Monson & L. Sumner (Eds.), *The desert bighorn: Its life history, ecology and management* (p. 370). Univ. Arizona Press.

Valdés-Alarcón, M., & Segundo-Galán, M. (2011). Estrategias de conservación en México para el borrego cimarrón (Ovis canadensis) y el berrendo (Antilocapra americana). In O. Sánchez, P. Zamorano, E. Peters, & H. Moya (Eds.), *Temas sobre Conservación de Vertebrados en México* (pp. 277–309). INECC-SEMARNAT. http://www2.inecc.gob.mx/publicaciones/libros/646/estrategias.pdf

van Mierlo, B., & Beers, P. J. (2020). Understanding and governing learning in sustainability transitions: A review. *Environmental Innovation and Societal Transitions*, *34*, 255–269. https://doi.org/10.1016/j.eist.2018.08.002

Velazquez, A., & Heil, G. W. (1996). "Habitat suitability study for the conservation of the volcano rabbit (Romerolagus diazi). *Journal of Applied Ecology*, 543–554.

Villarreal, G. (2012). *Introducción al manejo y aprovechamiento sustentable de la fauna silvestre en ranchos ganaderos diversificados*.

Walker, B., Gunderson, L., Kinzig, A., Folke, C., Carpenter, S., & Schultz, L. (2006). A handful of heuristics and some propositions for understanding resilience in social-ecological systems. *Ecology and Society*, *11*(1). https://doi.org/[online] URL:http://www.ecologyandsociety.org/vol11/iss1/art13/

Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, Adaptability and Transformability in Social – ecological Systems. *Ecology and Society*, *9*(2), 5. https://doi.org/10.1103/PhysRevLett.95.258101

Walker, B., & Salt, D. (2006). *Resilience Thinking: Sustaining Ecosystems and People in a Changing World*. Island Press.
Walker, B., & Salt, D. (2012). *Resilience Practice. Building Capacity to Absorb Disturbance and Mantain Function*. Islandpress.
Wang, T., Campbell, E. M., O'Neill, G. A., & Aitken, S. N. (2012). Projecting future distributions of ecosystem climate niches: Uncertainties and management applications. *Forest Ecology and Management*, *279*, 128–140. https://doi.org/10.1016/j.foreco.2012.05.034
Westley, F., Olsson, P., Folke, C., Homer-Dixon, T., Vredenburg, H., Loorbach, D., Thompson, J., Nilsson, M., Lambin, E., Sendzimir, J., Banerjee, B., Galaz, V., & van der Leeuw, S. (2011). Tipping toward sustainability: Emerging pathways of transformation. *Ambio*, *40*(7), 762–780. https://doi.org/10.1007/s13280-011-0186-9
Weyant, J., Davidson, O., Dowlatabadi, H., Edmonds, J., Grubb, M., Parson, E. A., Richels, R., Rotmans, J., Shukla, P., Tol, R. S. J., Cline, W., & Fankhauser, S. (1996). Integrated assessment of climate change: An overview and comparison of approaches and results. In J. P. Bruce, H. L. Haites, & E. F. Haites (Eds.), *Economic and Social Dimensions of Climate Change* (pp. 371–393). IPCC, Cambridge University Press.
Whiting, J., Bleich, R., Vernon, T., Bowyer, T., & Larsen, R. (2012). WATER AVAILABILITY AND BIGHORN SHEEP: LIFE-HISTORY CHARACTERISTICS AND PERSISTENCE OF POPULATIONS. In J. A. Daniels (Ed.), *Advances in Environmental Research.* Nova Science Publishers, Inc.
Wiek, A., Withycombe, L., & Redman, C. L. (2011). Key competencies in sustainability: A reference framework for academic program development. *Sustainability Science*, *6*(2), 203–218. https://doi.org/10.1007/s11625-011-0132-6
Wilder, B. T., Betancourt, J. L., Epps, C. W., Crowhurst, R. S., Mead, J. I., & Ezcurra, E. (2014). Local extinction and unintentional rewilding of bighorn sheep (Ovis canadensis) on a Desert Island. *PLoS ONE*, *9*(3). https://doi.org/10.1371/journal.pone.0091358
Williams, B. K., & Brown, E. D. (2014). Adaptive management: From more talk to real action. *Environmental Management*, *53*(2), 465–479. https://doi.org/10.1007/s00267-013-0205-7
Williams, B. K., & Brown, E. D. (2016). Technical challenges in the application of adaptive management. *Biological Conservation*, *195*, 255–263. https://doi.org/10.1016/j.biocon.2016.01.012
Zhong, L., Ma, Y., & Salama, M. S. (2010). Assessment of vegetation dynamics and their response to variations in precipitation and temperature in the Tibetan Plateau. *Climatic Change*, *103*, 519–535.

V. DISCUSIÓN

Muchos de los trabajos de investigación en torno al aprovechamiento del borrego cimarrón se han enfocado en un solo aspecto del sistema de aprovechamiento. Se han hecho esfuerzos muy valiosos por analizar los aspectos sociales (ganadería, agricultura) que afectan a la calidad del hábitat de la especie (Saavedra et al., 1999; Valdés-Alarcón & Segundo-Galán, 2011). Además de aquellos enfocados en la alimentación (O´Farril, 2003; Tarango et al., 2006); en la estructura poblacional; en la genética poblacional; en el hábitat (Alvarez-Cárdenas et al., 2009; Contreras & Espinosa, 2010; DeCesare & Pletscher, 2006; Escobar-Flores et al., 2015; González-Saldívar et al., 2012; Guerrero-Cárdenas et al., 2003; Heffelfinger & Marquez-Muñoz, 2005; Lindig et al., 2006; Manterola, 2001; Manterola y Piña, 1999; Mckinney et al., 2003; Mesa, 2013; Rodríguez-Ríos & García-Páez, 2017; Román, 2012; Ruíz, 2014; Saavedra et al., 1999; SAGARHPA, 2012; Schoenecker, 2004); en las enfermedades (Mckinney et al., 2003); en la sobrevivencia ante estrés hídrico (Colchero et al., 2009), entre otras. Para el caso de las poblaciones de borrego cimarrón en territorio mexicano existen trabajos que analizan esquemas de aprovechamiento de la especie con un enfoque de conservación (Huerta-García et al., 2015; Valdés-Alarcón & Segundo-Galán, 2011) e incluso en términos de derrama económica (Huerta-García et al., 2015); evaluación de las UMAs (SEMARNAT, 2012). Sin embargo, hasta el momento no se han encontraron trabajos que hayan integrado las dimensiones ecológica y socioeconómica en torno a la actividad cinegética y mucho menos trabajos que exploren los efectos del cambio climático en la estrategia/política de aprovechamiento de la especie. La falta de este tipo de investigación responde en gran medida a que los esfuerzo de formalizar la interdependencia o entrelazamiento de los SSEs plantea desafíos en la logística de obtención de datos y recursos para obtener datos empíricos. Además, se suma el desafío de comprender y gestionar sistemas de aprovechamiento ya sean terrestres o acuáticos debido a su dinamismo inherente.

1. Aportación metodológica

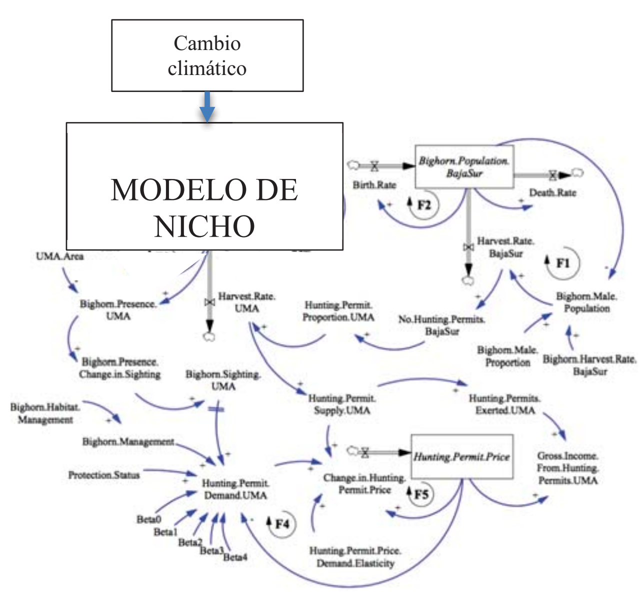
El método de DS implementado en el desarrollo del modelo de simulación, permitió formalizar y operacionalizar las relaciones, retroalimentaciones e interacciones socio-ecológicas que determinan el estado del SSE frente al cambio climático. Este resultado va más allá de un modelo ecológico que incorpora la acción humana como variable externa, o un modelo económico que considera a los ecosistemas como un insumo para una función de producción.

Este trabajo también permitió identificar los desafíos y oportunidades en la implementación de modelos computacionales de simulación para el análisis en SSEs. En primer lugar, los modelos de DS tradicionalmente no requieren investigación de campo (entrevistas o encuestas) para generar los diagramas causales y de flujo del sistema que analizan, generalmente se plantean los componentes y relaciones entre ellos basados en la literatura. Sin embargo, en esta investigación, la interacción con los agentes (ejidatarios, entidades federales (CONAMP y expertos) del sistema permitió la coproducción del modelo en el cual se plasma la percepción de los agentes sobre la problemática más importante que ellos identifican (el cambio climático). Al respecto, (Schlüter, Müller, et al., 2019) enfatizan el potencial que tiene la coproducción de modelos computacionales ya que mejora el entendimiento del sistema en general, así como el entendimiento del problema de acuerdo con la percepción de los participantes. Esto también incrementa el desarrollo de estrategias para resolverlas y también facilita la exploración de probables consecuencias socio-ecológicas en las decisiones o políticas (Lynam et al., 2007).

Adicionalmente, la modelación desde el enfoque de DS ayudó a identificar la importancia de capturar con mayor detalle o "realismo" la dinámica de la especie ante los efectos del cambio climático. Como estrategia metodológica para incrementar el "realismo" en el modelo de DS, este trabajo no solo recurrió al uso de ecuaciones diferenciales o integrales como tradicionalmente se diseñan estos modelos, también se empleó el uso de un modelo de aptitud de hábitat o modelo de nicho ecológico del borrego cimarrón para integrar los desafíos del cambio climático en el SSE. (Abbot & Hadžikadić, 2016) señalan que la combinación o hibridación de enfoques de modelación contribuye a reducir el nivel de abstracción que presentan los modelos basados en la DS y a incrementar la comprensión de las retroalimentaciones sociales y económicas en los modelos frente a estresores externos (en este caso, el cambio climático). La modelación de nicho ecológico se considera un método que permite estimar con mayor rigor los efectos del cambio climático en la aptitud del hábitat de la especie a través de un índice el cual, toma en cuenta los rangos de tolerancia de la especie en la región de interés y las proyecciones de cambio climático desarrolladas por distintos grupos de investigación alrededor del globo. Este método se ha implementado con objetivos de conservación en diferentes especies (Hirzel et al., 2006; Velazquez & Heil, 1996).

Adicionalmente, se identificó que la dinámica de oferta y demanda de permisos de cacería requiere mayor detalle. Se propone que, para mejorar el modelo en una siguiente fase, se pueden estimar de manera rigurosa las elasticidades de la demanda a través de la disponibilidad a pagar por parte de los cazadores.

Una posible expansión del modelo de simulación planteado en este trabajo de investigación supone el desarrollo de un Modelo Integrado de Evaluación (MIE), el cual podría integrar vincular (comunicar) al modelo de nicho ecológico con el modelo de DS a través de la sustitución de la variable de estado que caracteriza la dinámica de la población de borrego cimarrón en el ejido Bonfil por el valor de salida (índice de aptitud de hábitat) en el polígono de cada UMA de borrego cimarrón y ejidos (Figura 1). Es decir, expandir el MIE a los ejidos que realizan esta actividad en el país.



2. Aportación en la gestión de la resiliencia y sostenibilidad del sistema de aprovechamiento del borrego cimarrón en México

2.1. Estrategias o políticas de gestión adaptativas

El manejo de la vida silvestre actualmente define la tasa de extracción basándose solo en el censo de población total en BCS y no considera las implicaciones de la variabilidad de la precipitación (en la población de borrego cimarrón o en el daño a los ingresos de los ejidatarios), lo que reduce la capacidad de los ejidatarios para prepararse y adaptarse a los desafíos planteados por este factor estresante específico. Esta característica convierte al sistema de aprovechamiento en un SSE no resiliente.

El análisis exploratorio del sistema de aprovechamiento del borrego cimarrón sugiere que la esfera o subsistema ecológico cruzará su umbral en un período de tiempo determinado, dependiendo de la extensión y la intensidad del factor estresante (capítulo 2, Tabla 1). En todos los casos, se necesita la implementación de una estrategia de gestión alternativa y adaptativa para atender la sostenibilidad y resiliencia del SSE en el tiempo (capítulo 2, Tabla 1).

Además, la resiliencia se mide no solo identificando umbrales sino también en función del desempeño óptimo de ambos subsistemas al mismo tiempo y en función de la implementación de diferentes estrategias de adaptación. Este hallazgo implica que la medición de la resiliencia socio-ecológica tiene desafíos particulares para integrar a ambas dimensiones o esferas (Carpenter & Gunderson, 2001) al tratarse de una capacidad medida en términos dinámicos que puede identificar umbrales e incorporar escenarios de estrategias o políticas de gestión adaptativa.

2.2. Análisis espacial de la aptitud del hábitat del borrego cimarrón

Los resultados sobre polígonos con alta aptitud de hábitat son particularmente importantes para la gestión espacial del sistema de aprovechamiento del borrego cimarrón. La identificación de los posibles hábitats futuros podría ayudar a los ejidatarios y tomadores de decisiones a encontrar formas de priorizar las acciones de conservación en los paisajes de los que dependen. El conocimiento de la aptitud del hábitat basado en el cambio climático puede permitir que los ejidatarios y los responsables de la toma de decisiones concentren esfuerzos adicionales en lugares con la mayor probabilidad de éxito en la conservación de la especie frente al cambio climático. Comprender qué poblaciones están bajo el mayor estrés climático también podría ser de vital importancia en las próximas décadas para anticipar las acciones de conservación y gestión de estos sistemas de aprovechamiento. Por lo tanto, los analistas pueden ayudar a los tomadores de decisiones a distinguir las condiciones futuras en las que sus estrategias o políticas funcionarán bien de aquellas en las que tendrán un desempeño deficiente en términos de sostenibilidad socio-ecológica. Esta información puede ayudar a los tomadores de decisiones a identificar, evaluar y elegir estrategias o políticas robustas con un mejor desempeño en una amplia gama de futuros

Para futuras reintroducciones del borrego cimarrón, los ejidatarios deben considerar la precipitación esperadas dentro de los parámetros de elevación de la cadena montañosa en la cual se ubica geográficamente su ejido. Es de particular interés la identificación y protección temprana de refugios de hábitat idóneo para plantear estrategias o políticas de gestión. Por ejemplo, definir áreas en las que futuras poblaciones de borrego cimarrón podrían aprovecharse o incluso áreas que pueden emplearse como corredores de dispersión. Otra estrategia o política puede incluir la adquisición de tierras de conservación con mayor potencial para albergar refugios (Tingstad et al., 2017). En este contexto, los ejidatarios pueden considerar la posibilidad de trasladar individuos de borrego cimarrón entre áreas geográficas idóneas. Aunque la translocación es una estrategia de manejo controvertida con enfermedades inherentes y riesgos genéticos asociados, las poblaciones de borrego cimarrón se han translocado con éxito en las islas Tiburón y Carmen. Estas experiencias han demostrado que es posible hacer una contribución significativa en la conservación y el manejo sostenible de las especies. Lo cual supone también la sostenibilidad del SSE.

Estas estrategias juegan un papel importante tanto en la conservación de especies como en los hogares rurales cuando los ejidatarios obtienen una contribución económica importante al manejar esas poblaciones de manera sostenible. Por lo tanto, evaluar los efectos del cambio climático y la variabilidad en las poblaciones es esencial para la gestión sostenible y resiliente de los ecosistemas y la biodiversidad (Saba et al., 2012b) y también para la sostenibilidad y resiliencia de los medios de vida locales. Algunos estudios han evaluado los impactos del cambio climático y la variabilidad en los recursos que sustentan especies de vida silvestre económicamente importantes (Chidumayo, 2011), especialmente en la pesca (Islam et al., 2014b; Sumaila et al., 2011b). Sin embargo, los impactos del cambio climático en la biodiversidad global y cómo las especies biológicas pueden (o no) adaptarse aún no se han cuantificado (Advani, 2014).

3. Desafíos en la implementación de modelos integrados de evaluación para el análisis robusto de la resiliencia socio-ecológica.

Una evaluación está integrada cuando presenta un conjunto de información más amplio que el que normalmente se deriva de una actividad de investigación estándar o un solo enfoque (i.e. económico o ecológico). Debido a que las evaluaciones integradas reúnen y resumen información de diversos campos de estudio, a menudo se utilizan como herramientas para ayudar a los tomadores de decisiones a comprender problemas ambientales muy complejos.

Las dos características esenciales de una evaluación integrada del cambio climático son 1) que busca brindar información útil a los tomadores de decisiones en lugar de simplemente promover la comprensión por sí misma; y 2) que reúne un conjunto más amplio de áreas, métodos, estilos de estudio o grados de certeza, de lo que típicamente caracterizaría un estudio del mismo tema dentro de los límites de una sola disciplina de investigación.

Los modelos de evaluación integrados generalmente incluyen modelos de ciencias físicas y sociales que consideran variables demográficas, ecológicas, políticas y económicas, escenarios de emisiones, además de modelos del sistema climático físico. En este contexto, uno de los desafíos que enfrentó este proyecto fue el acceso a la capacidad de cómputo necesaria para procesar grandes cantidades de datos (1.3 TB) dado que fue necesario el uso de:

- Modelos de circulación general (GCMs)
- Escenarios de emisiones (RCPs)
- Datos socioeconómicos
- Datos poblacionales

La importancia de integrar la mayor cantidad de información disponible (GCMs, RCPs) radica en la diversidad de supuestos que integran. Estos modelos no solo deben proyectar cómo cambiará el clima en el futuro, sino que también deben anticipar cómo evolucionará la sociedad independientemente de si el clima cambia. Se utilizan diferentes supuestos sobre la tasa de crecimiento de la producción económica, la población y el uso de combustibles fósiles; así como diferentes supuestos sobre cómo responderá el ambiente al cambio climático. Dada la incertidumbre asociada, es deseable generar un análisis lo más robusto posible.

El modelo integrado de evaluación que se plantea en una próxima etapa de este proyecto consta de alrededor de 3.5 TB de información, la cual debe ser procesada. El requerimiento computacional que logró satisfacer las necesidades de este estudio durante la implementación del modelo de disponibilidad de hábitat fue un servidor de 100 núcleos y el tiempo total para generar los resultados del modelo fue de 24 horas continuas.

VI. CONCLUSIONES

Se reconoce la necesidad de mirar más allá de la capacidad de resiliencia específica en un solo ejido, y para hacerlo, primero es importante mejorar nuestra comprensión sistémica con un enfoque socio-ecológico. El método de modelación de DS permitió sentar la base para la futura expansión del modelo hasta donde los objetivos de las nuevas preguntas de investigación lo requieran. La importancia de este estudio radica en la incorporación de la teoría de la resiliencia en SSEs en la modelación dinámica empleando datos empíricos para explorar las disyuntivas en el aprovechamiento sostenible de una especie de vida libre e informar en la planificación de su aprovechamiento bajo condiciones de estrés hídrico en la región, lo cual implicó la identificación de aspectos críticos o umbrales en la gestión.

Actualmente, el sistema de aprovechamiento de borrego cimarrón en México no cuenta con una estrategia enfocada en enfrentar las complicaciones socio-ecológicas que el cambio climático podría generar en el aprovechamiento sostenible de la especie en el futuro. Sin embargo, en términos generales, la población de borrego cimarrón en Baja California Sur es particularmente susceptible a los periodos más secos del año. Debido a la ausencia de lluvia en este periodo, la población se mueve en busca de zonas menos cálidas y con más probabilidad de encontrar agua y alimento. Por lo tanto, la exploración temprana de circunstancias adversas para la conservación y aprovechamiento de la especie es de particular importancia para su gestión. Además, dado que el ingreso por venta de los permisos de cacería es importante para los hogares de socios de la UMA, el conocimiento sobre las posibles implicaciones del cambio climático en la población de esta especie es de mucha utilidad, principalmente para el diseño de estrategias o políticas de manejo que logren adaptarse a las condiciones cambiantes del clima y para poder mantener los beneficios (la sostenibilidad) tanto socioeconómicos como de conservación de una especie emblemática. Al respecto, el modelo exploratorio dinámico, sugirió que, ante un estrés hídrico muy prolongado, la especie tenderá a migrar hacia zonas con mejores condiciones. Por su parte el modelo de nicho ecológico confirma que la existencia de precipitación en los meses más secos es un factor muy importante para la especie, de tal forma que, es poco probable encontrarla en zonas donde la ausencia de precipitación es muy prolongada. En un escenario en el que el estrés hídrico se prolonga 10 años, la interrupción de la cacería deportiva no es suficiente para permitir la recuperación de la población de borrego cimarrón en Baja California Sur. El esfuerzo de las estrategias o políticas de manejo de la especie y gestión del sistema de aprovechamiento bajo circunstancias muy extremas se tendría que enfocar en la conservación implementando estrategias o políticas alternas ya probadas con éxito para la misma especie tales como: la reintroducción o translocación. Por lo tanto, se identificó que es igualmente importante el planteamiento detallado de posibles estrategias de política alternas para el manejo y gestión de la resiliencia y sostenibilidad de estos sistemas.

Las tendencias actuales en el uso de los datos a través de técnicas como la minería de datos, algoritmos de inteligencia artificial, aprendizaje de máquina hacen posible un análisis robusto de problemas complejos, y generan un nicho de oportunidad para el desarrollo de modelos integrados de evaluación. Sin embargo, la inversión en capital humano y capacidad computacional siguen siendo altos. Actualmente, los científicos de datos tienen perfiles académicos multidisciplinarios, lo cual sigue siendo costoso en términos de inversión en capital humano. Además, no todos los departamentos de ciencias sociales cuentan con un área con las capacidades computacionales requeridas para la implementación de estas técnicas. Por otro lado, en términos de obtención de datos de fuentes primarias, se observó que existe un área de oportunidad en los ejidos de BCS que pagan por el monitoreo aéreo cada dos años. Dado que no cuentan con una base de datos (en papel o digital), esto los limita en su capacidad de respuesta cuando es necesario el uso de los datos poblacionales para toma de decisiones consensuadas internamente, para la entrega de los informes anuales en tiempo y forma, e incluso para solicitar análisis externos de sus datos (consultoría).

Se concluye que el desarrollo de modelos numéricos de simulación que permitan el uso de toda la información disponible y que permitan la exploración de las trayectorias de los SSEs ante la influencia de sus principales estresores es una forma de sumar esfuerzos en el diseño de políticas adaptativas para impulsar la sostenibilidad socio-ecológica de los sistemas de aprovechamiento de recursos naturales frente al cambio climático (W. Adger, 2000; Armitage et al., 2012; Nelson et al., 2007) . Un área de investigación medular para las ciencias de la sostenibilidad (Kates, 2001).

VII. REFERENCIAS

Abbot, R., & Hadžikadić, M. (2016). *Complex Adaptive Systems, Systems Thinking, and Agent-Based Modeling*. SpringerLink.

Adger, W. (2000). Social and Ecological resilience, are they related? *Progress in Human Geography*, *24*, 346–364. https://doi.org/10.1191/030913200701540465

Adger, W. N. (2010). Social Capital, Collective Action, and Adaptation to Climate Change 1. *Economic Geography*.

Advani, N. (2014). *Climate Change Vulnerability Assessment for Species*. https://doi.org/10.13140/RG.2.1.3613.5522

Allen, C. R., & Garmestani, A. S. (2015). *Adaptive Management of Social-Ecological Systems.* . SpringerLink.

Allouche, O., Tsoar, A., & Kadmon, R. (2006). Assessing the accuracy of species distribution models: Prevalence, kappa and the true skill statistic (TSS). *Journal of Applied Ecology*, *43*(6), 1223–1232. https://doi.org/10.1111/j.1365-2664.2006.01214.x

Alvarez-Cárdenas, S., Galina-Tessaro, P., Díaz-Castro, S., Guerrero-Cárdenas, I., Castellanos-Vera, A., Mesa-Zavala, E., Investigaciones, C. de, No, S. C. M. B., Palo, P., Rita, D. S., Paz, L., & Sur, B. C. (2009). Evaluación de elementos estructurales del hábitat del borrego cimarrón en la Sierra del Mechudo , Baja California Sur , México. *Tropical Conservation Science*, *2*(2), 189–203.

Andrew, N. (1994). *Demography and Habitat Use of Desert-Dwelling Mountain Sheep in the East Chocolate Mountains, Imperial County, California*. University of Rhode Island.

Armitage, D., Béné, C., Charles, A. T., Johnson, D., & Allison, E. H. (2012). The interplay of well-being and resilience in applying a social- ecological perspective. *Ecology and Society*, *17*(4). https://doi.org/10.5751/ES-04940-170415

Ashcroft, M. B. (2010). Identifying refugia from climate change. *Biogeography*, *37*, 1407–1413.

Avila-Foucat, V. S., & Pérez-Campuzano, E. (2015). Municipality socioeconomic characteristics and the probability of occurrence of Wildlife Management Units in Mexico. *Environmental Science and Policy*, *45*, 146–153. https://doi.org/10.1016/j.envsci.2014.08.005

Bálint, M., Domisch, S., Engelhardt, C. H. M., Haase, P., Lehrian, S., Sauer, J., Theissinger, K., Pauls, S. U., & Nowak, C. (2011). Cryptic biodiversity loss linked to global climate change. *Nature Climate Change*, *1*(6), 313–318. https://doi.org/10.1038/nclimate1191

Bammer, G. (2005). Guiding principles for integration in natural resource management (NRM) as a contribution to sustainability. *Australasian Journal of Environmental Management*, *12*(SUPPL.1), 5–7. https://doi.org/10.1080/14486563.2005.9725099

Biggs, H., Pollard, S., & Toit, D. (2015). SYSTEMIC LINKS BETWEEN SOCIETY , WETLANDS AND WOODLANDS - THE BUSHBUCKRIDGE CASE. *UNPUBLISHED*, *October*, 246–256.

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E. L., BurnSilver, S., Cundill, G., Dakos, V., Daw, T. M., Evans, L. S., Kotschy, K., Leitch, A. M., Meek, C., Quinlan, A., Raudsepp-Hearne, C., Robards, M. D., Schoon, M. L., Schultz, L., & West, P. C.

(2012). Toward Principles for Enhancing the Resilience of Ecosystem Services. *Annual Review of Environment and Resources*, *37*(1), 421–448. https://doi.org/10.1146/annurev-environ-051211-123836

Binder, C. R., Hinkel, J., Bots, P. W. G., & Pahl-Wostl, C. (2013). Comparison of frameworks for analyzing social-ecological systems. *Ecology and Society*, *18*(4). https://doi.org/10.5751/ES-05551-180426

Brewer, G. D. (1999). The Challenges of Interdisciplinarity. *Policy Sciences*, *32*(4), 327–337. https://doi.org/10.1023/A:1004706019826

Bryant, B. P., & Lempert, R. J. (2010). Thinking Inside the Box: A Participatory, Computer- Assisted Approach to Scenario Discovery. *Gical Forecasting and Social Change*, *77*(1), 34–39.

Burgos, A., & Velázquez, A. (2019). A Territory Oriented Approach to Operationilize Sustainable Management. *Global Journal of Human Social Science*, *11*.

Carabias, J., Sarukhán, J., de la Maza, J., & Galindo, C. (2010). Patrimonio Natural de México. Cien casos de éxito. In *Patrimonio natural de México. Cien casos de éxito*.

Carpenter, S. R., Arrow, K. J., Barrett, S., Biggs, R., Brock, W. A., Crépin, A. S., Engström, G., Folke, C., Hughes, T. P., Kautsky, N., Li, C. Z., Mccarney, G., Meng, K., Mäler, K. G., Polasky, S., Scheffer, M., Shogren, J., Sterner, T., Vincent, J. R., … de Zeeuw, A. (2012). General resilience to cope with extreme events. *Sustainability*, *4*(12), 3248–3259. https://doi.org/10.3390/su4123248

Carpenter, S. R., Westley, F., & Turner, M. G. (2005). Surrogates for resilience of social-ecological systems. In *Ecosystems* (Vol. 8, Issue 8, pp. 941–944). https://doi.org/10.1007/s10021-005-0170-y

Carpenter, S., Walker, B., Anderies, J. M., & Abel, N. (2001). From Metaphor to Measurement: Resilience of What to What? *Ecosystems*, *4*(8), 765–781. https://doi.org/10.1007/s10021-001-0045-9

Carpenter, Stephen., & Gunderson, Lance. (2001). Coping with Collapse: Ecological and Social Dynamics in Ecosystem Management. *BioScience*, *51*(6), 451. https://doi.org/10.1641/0006-3568(2001)051[0451:CWCEAS]2.0.CO;2

Ceballos, G., & Oliva, G. (2005). *Los mamíferos silvestres de México*. CONABIO—Fondo de Cultura Económica.

Cheung, W., Jones, M., & Lam, V. (2016). Transform high seas management to build climate resilience in marine seafood supply. *Fish and Fisheries*.

Chidumayo, Emmanuel. (2011). *Climate change and african forest and wildlife resources*. African Forest Forum.

Cilliers, P., Biggs, H. C., Blignaut, S., Choles, A. G., Jewitt, G. P. W., & Roux, D. J. (2013). Complexity , Modeling , and Natural Resource Management. *Ecology and Society*, *18*(3).

Colchero, F., Medellin, R. A., Clark, J. S., Lee, R., & Katul, G. G. (2009). Predicting population survival under future climate change: Density dependence, drought and extraction in an insular bighorn sheep. *Journal of Animal Ecology*, *78*(3), 666–673. https://doi.org/10.1111/j.1365-2656.2009.01528.x

Conagua. (2012). *Atlas del agua en México 2012*. https://doi.org/ISBN: 978-607-8246-29-8

Contreras, A., & Espinosa, A. (2010). Evaluación de hábitat para la restauración del borrego cimarrón (Ovis canadensis) en Coahuila, México. *Redalyc*, *13*(1), 78–86.

Cumming, G. S., Barnes, G., Perz, S., Schmink, M., Sieving, K. E., Southworth, J., Binford, M., Holt, R. D., Stickler, C., & van Holt, T. (2005). An exploratory framework for the empirical measurement of resilience. *Ecosystems*, *8*(8), 975–987. https://doi.org/10.1007/s10021-005-0129-z

Cumming, G. S., & Peterson, G. D. (2017). Unifying Research on Social–Ecological Resilience and Collapse. In *Trends in Ecology and Evolution* (Vol. 32, Issue 9). https://doi.org/10.1016/j.tree.2017.06.014

D'Almeida Martins, R., & da Costa Ferreira, L. (2011). Opportunities and constraints for local and subnational climate change policy in urban areas: Insights from diverse contexts. *International Journal of Global Environmental Issues*, *11*(1), 37–53. https://doi.org/10.1504/IJGENVI.2011.040250

Danell, Kjell. (2006). *Large herbivore ecology, ecosystem dynamics and conservation*. Cambridge University Press.

Daw, Coulthard, Cheung, Brown, K., Abunge, C., Galafassi, D., Peterson, G., McClanahan, T., Omukoto, O., & Munyi, L. (2015). Evaluating taboo trade-offs in ecosystems services and human well-being. *PNAS*.

DeCesare, N., & Pletscher, D. H. (2006). Movements, Connectivity, and Resource Selection of Rocky Mountain Bighorn Sheep. *Journal of Mammalogy*, *87*(3), 531–538. https://doi.org/10.1644/05-MAMM-A-259R1.1

Ding, H., & Nunes, P. (2014). Modeling the links between biodiversity , ecosystem services and human wellbeing in the context of climate change : Results from an econometric analysis of the European forest ecosystems. *Ecological Economics*, *97*, 60–73. https://doi.org/10.1016/j.ecolecon.2013.11.004

Douglas, C. L., & Leslie, D. M. (1983). Influence of Weather and Density on Lamb Survival of Desert Mountain Sheep. *He Journal of Wildlife Management* , *50*, 153–156.

Dreiss, L. M., Hessenauer, J. M., Nathan, L. R., O'Connor, K. M., Liberati, M. R., Kloster, D. P., Barclay, J. R., Vokoun, J. C., & Morzillo, A. T. (2017). Adaptive Management as an Effective Strategy: Interdisciplinary Perceptions for Natural Resources Management. *Environmental Management*, *59*(2), 218–229. https://doi.org/10.1007/s00267-016-0785-0

Dreiss, L. M., Lacey, L. M., Weber, T. C., Delach, A., Niederman, T. E., & Malcom, J. W. (2022). Targeting current species ranges and carbon stocks fails to conserve biodiversity in a changing climate: Opportunities to support climate adaptation under 30 × 30. *Environmental Research Letters*, *17*(2). https://doi.org/10.1088/1748-9326/ac4f8c

Duncan, D. H., & Wintle, B. A. (2008). Towards Adaptive Management of Native Vegetation in Regional Landscapes. In C. W. Pettit C., Bishop I., Lowell K., Pullar D., & Duncan D. (Eds.), *Landscape Analysis and Visualisation. Lecture Notes in Geoinformation and Cartography.* (pp. 160–181). https://doi.org/https://doi.org/10.1007/978-3-540-69168-6_9

Escobar-Flores, J. G., Alvarez-Cardenas, S., Valdez, R., Torres-Rodriguez, J., Díaz-Castro, S., Castellanos-Vera, A., & Martinez-Gallardo, R. (2015). Detección de las preferencias de hábitat del borrego cimarrón (Ovis canadensis cremnobates) en Baja California, mediante Técnicas de Teledetección Satelital. *Therya*, *6*(3), 519–534. https://doi.org/10.12933/therya-15-284

Fischbach, J. R., Johnson, D. R., & Groves, D. G. (2019). Flood damage reduction benefits and costs in Louisiana's 2017 coastal master plan. . *Environ. Res. Commun*.

Fischer, J., Gardner, T. A., Bennett, E. M., Balvanera, P., Biggs, R., Carpenter, S., Daw, T., Folke, C., Hill, R., Hughes, T. P., Luthe, T., Maass, M., Meacham, M., Norström, A. v., Peterson, G., Queiroz, C., Seppelt, R., Spierenburg, M., & Tenhunen, J. (2015). Advancing sustainability through mainstreaming a social-ecological systems perspective. *Current Opinion in Environmental Sustainability*, *14*, 144–149. https://doi.org/10.1016/j.cosust.2015.06.002

Folke, C. (2006). Resilience: The emergence of a perspective for social-ecological systems analyses. *Global Environmental Change*, *16*(3), 253–267. https://doi.org/10.1016/j.gloenvcha.2006.04.002

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

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2010). Resilience Thinking : Integrating Resilience , Adaptability and Transformability. *Ecology and Society*, *15*(4), 20.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., & Holling, C. S. (2004). Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology, Evolution, and Systematics*, *35*, 557–581. https://doi.org/10.1146/annurev.ecolsys.35.021103.105711

Folke, C., Jansson, Å., Rockström, J., Olsson, P., Carpenter, S. R., Stuart Chapin, F., Crépin, A. S., Daily, G., Danell, K., Ebbesson, J., Elmqvist, T., Galaz, V., Moberg, F., Nilsson, M., Österblom, H., Ostrom, E., Persson, Å., Peterson, G., Polasky, S., … Westley, F. (2011). Reconnecting to the biosphere. *Ambio*, *40*(7), 719–738. https://doi.org/10.1007/s13280-011-0184-y

Forrest, J. L., Wikramanayake, E., Shrestha, R., Areendran, G., Gyeltshen, K., Maheshwari, A., Mazumdar, S., Naidoo, R., Thapa, G. J., & Thapa, K. (2012). Conservation and climate change: Assessing the vulnerability of snow leopard habitat to treeline shift in the Himalaya. *Biological Conservation*, *150*(1), 129–135. https://doi.org/10.1016/j.biocon.2012.03.001

Forrester, J. W. (1994). System dynamics, systems thinking, and soft OR. *System Dynamics Review*, *10*(2).

Galvani, A. P., Bauch, C. T., Anand, M., Singer, B. H., & Levin, S. A. (2016). Human-environment interactions in population and ecosystem health. In *Proceedings of the National Academy of Sciences of the United States of America* (Vol. 113, Issue 51, pp. 14502–14506). National Academy of Sciences. https://doi.org/10.1073/pnas.1618138113

García, J. T., Jiménez, J., Mateo, R., & Arroyo, B. (2016). *Current Trends in Wildlife Research*. *1*, 283–293. https://doi.org/10.1007/978-3-319-27912-1

Garcia, R. A., Cabeza, M., Rahbek, C., & Araújo, M. B. (2014). Multiple dimensions of climate change and their implications for biodiversity. In *Science* (Vol. 344, Issue 6183). American Association for the Advancement of Science. https://doi.org/10.1126/science.1247579

Gedir, J. v, Cain, J. W., Swetnam, T. L., Krausman, P. R., & Morgart, J. R. (2020). Extreme drought and adaptive resource selection by a desert mammal. *Ecosphere*, *11*(17). https://doi.org/doi:e03175. 10.1002/ecs2.3175

González-Saldívar, F., Tarango-Arámbula, L. a, Cantú-Ayala, C., Uvalle-Sauceda, J., Marmolejo-Moncivais, J., & Ríos-Saldaña, C. (2012). Estudio Poblacional y de distribución del borrego cimarrón (Ovis canadensis mexicana , merriam , 1901) en Sonora. *Revista Mexicana de Ciencias Forestales*, *2*(4), 63–75.

Graziano, M. P., Deguire, A. K., & Surasinghe, T. D. (2022). Riparian Buffers as a Critical Landscape Feature: Insights for Riverscape Conservation and Policy Renovations. In *Diversity* (Vol. 14, Issue 3). MDPI. https://doi.org/10.3390/d14030172

Grinnell, J. (1917). The Niche-Relationships of the California Thrasher. *The Auk JSTOR*, *34*(4), 427–433.

Groves, D. G., Bonzanigo, L., Syme, J., Engle, N. L., & Rodriguez Cabanillas, I. (2019). *Preparing for Future Droughts in Lima, Peru: Enhancing Lima's Drought Management Plan to Meet Future Challenges. Washington, DC: World Bank*.

Groves, D. G., Kuhn, K., Fischbach, J. R., Johnson, D. R., & Syme, J. (2016). *Analysis to Support Louisiana's Flood Risk and Resilience Program and Application to the National Disaster Resilience Competition*.

Groves, D. G., & Lempert, R. J. (2007). A new analytic method for finding policy-relevant scenarios. *Global Environ. Change*, *17*, 73–85.

Guerrero-Cárdenas, I., Tovar-Zamora, I., & Álvarez-Cárdenas, S. (2003). Factores que afectan la distribución espacial del borrego cimarrón Ovis canadensis weemsi en la Sierra del Mechudo ,. *Anales Del Instituto de Biología, Universidad Nacional Autónoma de México, Serie Zoología*, *74*(195), 83–98.

Guerry, A. D., Polasky, S., Lubchenco, J., Chaplin-Kramer, R., Daily, G. C., Griffin, R., Ruckelshaus, M., Bateman, I. J., Duraiappah, A., Elmqvist, T., Feldman, M. W., Folke, C., Hoekstra, J., Kareiva, P. M., Keeler, B. L., Li, S., McKenzie, E., Ouyang, Z., Reyers, B., … Vira, B. (2015). Natural capital and ecosystem services informing decisions: From promise to practice. In *Proceedings of the National Academy of Sciences of the United States of America* (Vol. 112, Issue 24, pp. 7348–7355). National Academy of Sciences. https://doi.org/10.1073/pnas.1503751112

Guisan, A., Tingley, R., Baumgartner, J. B., Naujokaitis-Lewis, I., Sutcliffe, P. R., Tulloch, A. I. T., Regan, T. J., Brotons, L., Mcdonald-Madden, E., Mantyka-Pringle, C., Martin, T. G., Rhodes, J. R., Maggini, R., Setterfield, S. A., Elith, J., Schwartz, M. W., Wintle, B. A., Broennimann, O., Austin, M., … Buckley, Y. M. (2013). Predicting species distributions for conservation decisions. *Ecology Letters*, *16*(12), 1424–1435. https://doi.org/10.1111/ele.12189

Gunderson, L. H., & Holling, C. S. (2002). *Panarchy:Undestanding Transformations in Human and Natural Systems* (L. H. Gunderson & C. S. Holling, Eds.). Island Press.

Head, B. W., & Alford, J. (2015). Wicked Problems: Implications for Public Policy and Management. *Administration and Society*, *47*(6), 711–739. https://doi.org/10.1177/0095399713481601

Heffelfinger, J. R., & Marquez-Muñoz, E. (2005). Historical occurrence and distribution of desert bighorn sheep in Chihuahua , Mexico. *DESERT BIGHORN COUNCIL TRANSACTIONS*, *48*, 28–38.

Helena, C. (2020). *Translocación y reintroducción como estrategias complementarias para la conservación del endémico y críticamente amenazado Paujil de pico azul (Crax alberti)*.

Hilty, J., Worboys, G. L., Keeley, A., Woodley, S., Lausche, B., Locke, H., Carr, M., Pulsford, I., Pittock, J., White, J. W., Theobald, D. M., Levine, J., Reuling, M., Watson, J. E. M., Ament, R., & Tabor, G. M. (2020). *Guidelines for conserving connectivity through ecological networks and corridors Best Practice Protected Area Guidelines Series No. 30 Developing capacity for a protected planet*. www.iucn.org/pa_guidelines

Hirzel, A. H., Lay L., Helfer, V., Randin, C., & Guisan, A. (2006). Evaluating the ability of habitat suitability models to predict species presences.(2006): 142-152. *Ecological Modelling*, 142–152.

Hoegh-Guldberg, O., Kenned, E., Beyer, H., McClennen, C., & Possingham, H. (2018). Securing a Long-term Future for Coral Reefs. *Trends in Ecology & Evolution*, *33*(12), 936–944.

Holling, C. S. (2001). Understanding Complexity of Economic, Ecological, and Social Systems. *Ecosystems*, *4*, 390–405.

Huerta-García, A., Ramírez-Milanés, M. N., Valenzuela-Núñez, L. M., & Abad-Zavaleta, J. (2015). Aprovechamiento del borrego cimarrón (Ovis canadensis mexicana) en unidades de manejo del noreste de México. *Ecosistemas y Recursos Agropecuarios*, *2*(6), 339–347.

Hughes, T. P., Carpenter, S., Rockström, J., Scheffer, M., & Walker, B. (2013). Multiscale regime shifts and planetary boundaries. *Trends in Ecology and Evolution*, *28*(7), 389–395. https://doi.org/10.1016/j.tree.2013.05.019

Hull, V., Tuanmu, M.-N., & Liu, J. (2015). Ecology and Society: Synthesis of human-nature feedbacks. *Ecology and Society*, *20*(3), 17. http://www.ecologyandsociety.org/vol20/iss3/art17/

IPCC. (2021a). *IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou, Eds.). Cambridge University Press.

IPCC. (2021b). Technical Summary. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In *Climate Change 2021: The Physical Science Basis.*

Islam, M. M., Sallu, S., Hubacek, K., & Paavola, J. (2014a). Vulnerability of fishery-based livelihoods to the impacts of climate variability and change: Insights from coastal Bangladesh. *Regional Environmental Change*, *14*(1), 281–294. https://doi.org/10.1007/s10113-013-0487-6

Islam, M. M., Sallu, S., Hubacek, K., & Paavola, J. (2014b). Vulnerability of fishery-based livelihoods to the impacts of climate variability and change: Insights from coastal Bangladesh. *Regional Environmental Change*, *14*(1), 281–294. https://doi.org/10.1007/s10113-013-0487-6

Isley, S. C., Lempert, R. J., Popper, S. W., & Vardavas, R. (2015). The effect of near-term policy choices on long-term greenhouse gas transformation pathways. *Glob. Environ. Change*, *34*, 147–158.

Kalra, N., Hallegatte, S., Lempert, R., Brown, C., Fozzard, A., Gill, S., & Shah, A. (2014). *Agreeing on Robust Decisions New Processes for Decision Making Under Deep Uncertainty*. http://econ.worldbank.org.

Karger, D. N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R. W., Zimmermann, N. E., Linder, H. P., & Kessler, M. (2018). *Data from: Climatologies at high resolution for the earth's land surface areas*. https://doi.org/10.5061/dryad.kd1d4

Kasprzyk, J. R., Nataraj, S., Reed, P. M., & Lempert, R. J. (2013). Many objective robust decision making for complex environmental systems undergoing change. *Environ. Model. Softw.*, *42*, 55–71.

Kates. (2001). Sustainability Science. *Science*, *292*(5517), 641–642. https://doi.org/10.1126/science.1059386

Kengar, A., Vinayake, K., Mallia, J., Darade. M, Kumar, B., & Chahande, S. (2021). *Ecology Research* (A. Kengar, M. Darade, K. Vinayake, B. Kumar, J. Mallia, & S. Chahande, Eds.; Vol. 2).

Köberle, A. C., Vandyck, T., Guivarch, C., Macaluso, N., Bosetti, V., Gambhir, A., Tavoni, M., & Rogelj, J. (2021). The cost of mitigation revisited. In *Nature Climate Change*. Nature Research. https://doi.org/10.1038/s41558-021-01203-6

Kwakkel, J. H. (2017). The exploratory modeling workbench: an open source toolkit for exploratory modeling, scenario discovery, and (multiobjective) robust decision making. . *Environ. Model. Softw.* , *96*, 239–250.

Langridge, J., Sordello, R., & Reyjol, Y. (2020a). Outcomes of wildlife translocations in protected areas: what is the type and extent of existing evidence? A systematic map protocol. *Environmental Evidence*, *9*(1). https://doi.org/10.1186/s13750-020-00199-4

Langridge, J., Sordello, R., & Reyjol, Y. (2020b). Outcomes of wildlife translocations in protected areas: what is the type and extent of existing evidence? A systematic map protocol. *Environmental Evidence*, *9*(1). https://doi.org/10.1186/s13750-020-00199-4

Langridge, J., Sordello, R., & Reyjol, Y. (2021). Existing evidence on the outcomes of wildlife translocations in protected areas: a systematic map. *Environmental Evidence*, *10*(1). https://doi.org/10.1186/s13750-021-00236-w

Larson, A. M., & Ribot, J. C. (2007). The poverty of forestry policy: Double standards on an uneven playing field. *Sustainability Science*, *2*(2), 189–204. https://doi.org/10.1007/s11625-007-0030-0

Lee, R. (2003). A review of recent wild sheep surveys in Baja California Sur, Mexico. *Desert Bighorn Council Transaction*, *43*, 43–46.

Lee, R. (2008). Hunting as a Tool For Wildlife Conservation: The Case of Sheep Hunting in Mexico. In R. D. Baldus, G. R. Damm, & K. Wollscheid (Eds.), *Best Practices in Sustainable Hunting A Guide to Best Practices From Around the World*.

Lee, R. (2016). *Monitoreo Aéreo de la Población de Borrego Cimarron en Baja California Sur (2016). Reporte Técnico No Publicado*.

Lempert, R. (2015). Selection of climate policies under the uncertainties in the Fifth Assessment Report of the IPCC. *Nature Climate Change*, *5*(10), 937–943. https://doi.org/10.1038/nclimate2721

Lempert, R. J., & Groves, D. G. (2010). Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west. *Technol. Forecast. Soc. Change*, *77*, 960-974.

Lempert, R. J., Groves, D. G., Popper, S., & Bankes, S. C. (2006). A general, analytic method for generating robust strategies and narrative scenarios. *Manag. Sci.*, *52*, 514–528.

Lempert, R. J., Popper, S. W., & Bankes, S. C. (2003). *Shaping the next one hundred years : new methods for quantitative, long-term policy analysis and bibliography*. RAND.

Levin, S. (1998). The Ecosystems and Biosphere Complex Adaptive Systems. *Ecosystems*, 431–436.

Levin, S., Xepapadeas, T., Crépin, A.-S., Norberg, J., de Zeeuw, A., Folke, C., Hughes, T., Arrow, K., Barrett, S., Daily, G., Ehrlich, P., Kautsky, N., Mäler, K.-G., Polasky, S., Troell, M., Vincent, J. R., & Walker, B. (2013). Social-ecological systems as complex adaptive systems: modeling and policy implications. *Environment and Development Economics*, *18*(02), 111–132. https://doi.org/10.1017/S1355770X12000460

Lindig, R., Galindo, S., & Lara, S. (2006). Historical distribution of desert bighorn sheep (ovis canadensis mexicana) in Coahuila Mexico. *The Southwestern Naturalist*, *51*(4), 455–461. https://doi.org/10.1894/0038-4909(2006)51

Liu, J., Hull, V., Batistella, M., DeFries, R., Dietz, T., Fu, F., Hertel, T. W., Izaurralde, R. C., Lambin, E. F., Li, S., Martinelli, L. A., McConnell, W. J., Moran, E. F., Naylor, R., Ouyang, Z., Polenske, K. R., Reenberg, A., Rocha, G. de M., Simmons, C. S., … Zhu, C. (2013). Framing Sustainability in Telecoupled World. *Ecology and Society 18(2):*, *18*(12), 26. https://doi.org/. http://dx.doi.org/10.5751/ ES-05873-180226 Synthesis

López-Feldman, A., & Wilen, J. E. (2008). Poverty and spatial dimensions of non-timber forest extraction. *Environment and Development Economics*, *13*(05), 1–43. https://doi.org/10.1017/S1355770X08004518

Lynam, T., de Jong, W., Sheil, D., Kusumanto, T., & Evans, K. (2007). A review of tools for incorporating community knowledge, preferences, and values into decision making in natural resources management. *Ecology and Society* , *12*(1).

Maida, C. A., & Beck, S. (2018). *Global Sustainability and Communities of Practice* (1st ed.). Berghahn Books JSTOR.

Manterola, C. (2001). *Censo aéreo de poblaciones de borrego cimarrón (Ovis canadensis cremnobates) en Baja California , México*.

Manterola y Piña, C. (1999). Monitoreo de las poblaciones de borrego cimarrón (Ovis canadensis weemsi) en Baja California Sur, México. In *SNIB-CONABIO*.

Marchau, V. A. W. J., Walker, W. E., Bloemen, M., P. J. T., & Popper, S. W. (2019). Decision Making Under Deep Uncertainty. In V. A. W. J. Marchau, W. E. Walker, P. J. T. Bloemen, M., & S. W. Popper (Eds.), *The Oxford Handbook of Planning for Climate Change Hazards*. https://doi.org/10.1093/oxfordhb/9780190455811.013.50

Marchau, V., Walker, W. E., A.Bloemen, P. J., & Popper, S. W. (2019). *Decision Making under Deep Uncertainty*. Springer International Publishing. https://doi.org/10.1007/978-3-030-05252-2

Mayer, I. S., van Daalen, C. E., & Bots, P. W. G. (2004). Perspectives on policy analyses: A framework for understanding and design. In *International Journal of Technology, Policy and Management* (Vol. 4, Issue 2, pp. 169–191). Inderscience Publishers. https://doi.org/10.1504/IJTPM.2004.004819

Mckinney, T., Smith, T., & DeVos, J. (2003). Evaluation of Factors Potentially Influencing a Desert Bighorn Sheep Population. *The Wildlife Society*, *0173*, 1–36.

Medeiros, E. (2016). Is there a rise of the territorial dimension in the EU Cohesion Policy ? *Finisterra*.

Meltzer, R., & Schwartz, A. (2019). *Policy Analysis as Problem Solving: A Flexible and Evidence-Based Framework*. Routledge.

Mesa, E. (2013). *Diagnóstico del hábitat del borrego cimarrón en funcion de variables ambientales y actividades antropogénicas en la sierra El Mechudo Baja California Sur, México.* Centro de Investigaciones Biológicas del Noreste, S. C.

Milner-Gulland, E. J. (2012). Interactions between human behaviour and ecological systems. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*(1586), 270–278. https://doi.org/10.1098/rstb.2011.0175

Molina-Perez, E., Esquivel-Flores, O. A., & Zamora-Maldonado, H. (2020). Computational Intelligence for Studying Sustainability Challenges: Tools and Methods for Dealing With Deep Uncertainty and Complexity. *Frontiers in Robotics and AI*, *7*. https://doi.org/10.3389/frobt.2020.00111

Molina-Perez, E., Groves, D. G., Popper, S. W., Ramirez, A. I., & Crespo-Elizondo, R. (2019). *Developing a robust water strategy for Monterrey, Mexico : diversification and adaptation for coping with climate, economic, and technological uncertainties*.

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H., & Schwarz, N. (2013). Describing human decisions in agent-based models - ODD+D, an extension of the ODD protocol. *Environmental Modelling and Software*, *48*, 37–48. https://doi.org/10.1016/j.envsoft.2013.06.003

Murray, C., & Marmorek, D. (2003). Adaptive Management and Ecological Restoration. In P. Freiderici (Ed.), *Ecological Restoration of Southwestern Ponderosa Pine Forests* (pp. 417–428). Island Press.

Nelson, D. R., Adger, W. N., & Brown, K. (2007). Adaptation to Environmental Change: Contributions of a Resilience Framework. *Annual Review of Environment and Resources*, *32*(1), 395–419. https://doi.org/10.1146/annurev.energy.32.051807.090348

O´Farril, E. (2003). *Dieta y uso del hábitat del borrego cimarrón (Ovis canadensis mexicana) y el venado bura (Odocoileus hemionus sheldoni) en Isla Tiburón, Sonora, México*. Universidad Nacional Autónoma de México.

O'Higgins, T. G., Lago, M., & DeWitt, T. H. (2020). *Ecosystem-Based Management, Ecosystem Services and Aquatic Biodiversity* (T. G. O'Higgins, M. Lago, & T. H. DeWitt, Eds.). Springer. https://doi.org/https://doi.org/10.1007/978-3-030-45843-0

Oliver, K., & Cairney, P. (2019). The dos and don'ts of influencing policy: a systematic review of advice to academics. In *Palgrave Communications* (Vol. 5, Issue 1). Palgrave Macmillan Ltd. https://doi.org/10.1057/s41599-019-0232-y

Ordoñez-Matamoros. (2013). *Manual de Análisis y Diseño de Políticas Públicas*. Panamericana.

Ostrom, E. (2005). *Understanding Institutional Diversity*. Princeton University Press.

Ostrom, E. (2009). A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science*, *325*, 419–423.

Owen, G. (2020). What makes climate change adaptation effective? A systematic review of the literature. *Global Environmental Change*, *62*. https://doi.org/10.1016/j.gloenvcha.2020.102071

Palomo-Ramos, R., Ramos, P., Colima, G., & Arana, R. (n.d.). *REVISTA BIO CIENCIAS Translocation as a conservation tool for endangered tortoises in Mexico Las translocaciones como herramienta de conservación para las tortugas terrestres en México*. https://doi.org/10.15741/revbio.05.01.01

Parker, J., Simpson, G. D., & Miller, J. E. (2020). Nature-based solutions forming urban intervention approaches to anthropogenic climate change: A quantitative literature review. In *Sustainability (Switzerland)* (Vol. 12, Issue 18). MDPI. https://doi.org/10.3390/SU12187439

Pereira, H., Leadleyvania, P., & Proença, V. (2010). Scenarios for Global Biodiversity in the 21st Century. *Science*, *330*(6010).

Perry, D. C., Chaffee, C., Wigand, C., & Thornber, C. (2020). Implementing adaptive management into a climate change adaptation strategy for a drowning New England salt marsh. *Journal of Environmental Management*, *270*. https://doi.org/10.1016/j.jenvman.2020.110928

Peterson, T., & Anamza, T. (2015). Ecological niches and present and historical geographic distributions of species: a 15-year review of frameworks, results, pitfalls, and promises. *Folia Zoologica*, *64*(3), 207–217.

Phillips, S. J., Anderson, R. P., Dudík, M., Schapire, R. E., & Blair, M. E. (2017). Opening the black box: an open-source release of Maxent. *Ecography*, *40*(7), 887–893. https://doi.org/10.1111/ecog.03049

Phillips, S. J., & Dudík, M. (2008). *Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation*. https://doi.org/10.1111/j.2007.0906-7590.05203.x

Pires, A. P. F., Srivastava, D. S., Marino, N. A. C., Andrew, A., Macdonald, M., Figueiredo-Barros, M. P., & Farjalla, V. F. (2018). *Interactive effects of climate change and biodiversity loss on ecosystem functioning*.

Popper, S. W., Berrebi, C., Griffin, J., Crane, K., Light, T., & Daehner, E. M. (2009). *Natural Gas and Israel's Energy Future*.

Ramirez-Villegas, J., Devenish, F., & Cuesta, F. (2014). Using species distributions models for designing conservation strategies of Tropical Andean biodiversity under climate change. *Nature Conservation*, *22*(5), 391–404.

Ramos, P., Colima, G., & Arana, R. (2018). Translocation as a conservation tool for endangered tortoises in Mexico. *REVISTA BIO CIENCIAS* . https://doi.org/10.15741/revbio.05.01.01

Resilience Alliance. (2015). ASSESSING RESILIENCE IN SOCIAL-ECOLOGICAL SYSTEMS. *Stockholm University*, *June*, 1–53. http://www.stockholmresilience.org/21/research/what-is-resilience/research-background/research-framework/social-ecological-systems.html

Robinson, J. G., & Bennett, E. (2001). *Hunting for Sustainability in Tropical Forests* (J. G. Robinson & E. Bennett, Eds.; Vol. 39). Columbia University Press,.

Rodríguez-Ríos, E., & García-Páez, B. (2017). Valuing bushmeat for people living at a subsistence level: The case of *Cuniculus paca* meat in Flavio Alfaro, Manabí, Ecuador. *Human Dimensions of Wildlife*. https://doi.org/10.1080/10871209.2018.1419517

Román, R. (2012). *Densidad y estructura poblacional del Borrego Cimarrón (Ovis canadensis weemsi, Goldman, 1937) en la Isla "El Carmen", Baja California Sur, México*. Universidad Autónoma de Nuevo León.

Ruíz, E. (2014). *Estado actual de la población de borrego cimarrón (Ovis canadensis weemsi) En la UMA ejido La Purísima, Baja California Sur, México*. Universidad Nacional Autónoma de México.

Saavedra, E., Lee, R. M., de Vos, J. C., Schweinsburg, R. E., & Salazar, G. (1999). Relación Uso-Disponibilidad De Componentes Topográficos Y Un Modelo De Calidad Del Hábitat Para El Borrego Cimarrón, En Sonora, México. *Acta Zoológica Mexicana (Ns)*, *76*, 17–34.

Saba, V. S., Stock, C. A., Spotila, J. R., Paladino, F. v., & Tomillo, P. S. (2012a). Projected response of an endangered marine turtle population to climate change. *Nature Climate Change*, *2*(11), 814–820. https://doi.org/10.1038/nclimate1582

Saba, V. S., Stock, C. A., Spotila, J. R., Paladino, F. v., & Tomillo, P. S. (2012b). Projected response of an endangered marine turtle population to climate change. *Nature Climate Change*, *2*(11), 814–820. https://doi.org/10.1038/nclimate1582

SAGARHPA. (2012). Borrego cimarrón (Ovis canadensis mexicana): Resultados del monitoreo aéreo en el Estado de Sonora, México. Noviembre, 2012. In *SAGARHPA*. http://www.hunting.sonora.gob.mx/convenios/libro.pdf

Scarlett, L. (2013). Collaborative adaptive management: Challenges and opportunities. *Ecology and Society*, *18*(3). https://doi.org/10.5751/ES-05762-180326

Scheffer, M., & Carpenter, S. R. (2003). Catastrophic regime shifts in ecosystems: Linking theory to observation. *Trends in Ecology and Evolution*, *18*(12), 648–656. https://doi.org/10.1016/j.tree.2003.09.002

Schlüter, M., Müller, B., & Frank, K. (2019). The potential of models and modeling for social-ecological systems research: The reference frame ModSES. *Ecology and Society*, *24*(1). https://doi.org/10.5751/ES-10716-240131

Schlüter, M., Orach, K., Lindkvist, E., Martin, R., Wijermans, N., Bodin, Ö., & Boonstra, W. J. (2019). Toward a methodology for explaining and theorizing about social-ecological phenomena. *Current Opinion in Environmental Sustainability*, *39*, 44–53. https://doi.org/10.1016/j.cosust.2019.06.011

Schoenecker, K. A. (2004). Bighorn Sheep Habitat Studies , Population Dynamics , and Population Modeling in Bighorn Canyon National Recreation Area , 2000 – 2003. *Recreation*, 216.

Schwartz, M. (2012). Using niche models with climate projections to inform conservation management decisions. *Biological Conservation*, *155*, 149–156.

SEMARNAT. (2012). Estrategia Estatal Para la Conservación y Manejo Sustentable del Borrego Cimarrón (Ovis canadensis cremnobates) en Baja California. *SEMARNAT*, 91.

Seppelt, R., Müller, F., Schröder, B., & Volk, M. (2009). Challenges of simulating complex environmental systems at the landscape scale: a controversial dialogue between two cups of espresso . *Ecological Modeling*, *220*, 3481–3489.

Spencer, R., & Janzen, F. (2010). Demographic consequences of adaptive growth and the ramifications for conservation of long-lived organisms. *Biological Conservation*, *143*(9), 1951–1959.

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

Sumaila, U. R., Cheung, W. W. L., Lam, V. W. Y., Pauly, D., & Herrick, S. (2011a). Climate change impacts on the biophysics and economics of world fisheries. In *Nature Climate Change* (Vol. 1, Issue 9, pp. 449–456). https://doi.org/10.1038/nclimate1301

Sumaila, U. R., Cheung, W. W. L., Lam, V. W. Y., Pauly, D., & Herrick, S. (2011b). Climate change impacts on the biophysics and economics of world fisheries. In *Nature Climate Change* (Vol. 1, Issue 9, pp. 449–456). https://doi.org/10.1038/nclimate1301

Tarango, L. a., Krausman, P. R., Valdez, R., & Kattnig, R. M. (2006). Research observation: desert bighorn sheep diets in northwestern Sonora, Mexico. *Journal of Range Management Archives*, *55*(6), 530–534. https://doi.org/10.2307/4003995

Tingstad, A. H., Lempert, R. J., Moskwik, M., Warren, D. L., Parmesan, C., Mcginnis, S., & Ryu, Y. (2017). Demonstrating the Applicability of a Robust Decision Making (RDM) to Conservation Decision-Making Under Uncertain Future Climate: Pilot Study Using the Northern Pygmy Salamander (Desmognathus organi). In *Journal of Conservation Planning* (Vol. 13).

Turner, J. C., & Weaver, A. (1980). Water. In G. Monson & L. Sumner (Eds.), *The desert bighorn: Its life history, ecology and management* (p. 370). Univ. Arizona Press.

Valdés-Alarcón, M., & Segundo-Galán, M. (2011). Estrategias de conservación en México para el borrego cimarrón (Ovis canadensis) y el berrendo (Antilocapra americana). In O. Sánchez, P. Zamorano, E. Peters, & H. Moya (Eds.), *Temas sobre Conservación de Vertebrados en México* (pp. 277–309). INECC-SEMARNAT. http://www2.inecc.gob.mx/publicaciones/libros/646/estrategias.pdf

van Mierlo, B., & Beers, P. J. (2020). Understanding and governing learning in sustainability transitions: A review. *Environmental Innovation and Societal Transitions*, *34*, 255–269. https://doi.org/10.1016/j.eist.2018.08.002

Velazquez, A., & Heil, G. W. (1996). "Habitat suitability study for the conservation of the volcano rabbit (Romerolagus diazi). *Journal of Applied Ecology*, 543–554.

Villarreal, G. (2012). *Introducción al manejo y aprovechamiento sustentable de la fauna silvestre en ranchos ganaderos diversificados*.

Walker, B., Gunderson, L., Kinzig, A., Folke, C., Carpenter, S., & Schultz, L. (2006). A handful of heuristics and some propositions for understanding resilience in social-ecological systems. *Ecology and Society*, *11*(1). https://doi.org/[online] URL:http://www.ecologyandsociety.org/vol11/iss1/art13/

Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, Adaptability and Transformability in Social – ecological Systems. *Ecology and Society*, *9*(2), 5. https://doi.org/10.1103/PhysRevLett.95.258101

Walker, B., & Salt, D. (2006). *Resilience Thinking: Sustaining Ecosystems and People in a Changing World*. Island Press.

Walker, B., & Salt, D. (2012). *Resilience Practice. Building Capacity to Absorb Disturbance and Mantain Function*. Islandpress.

Wang, T., Campbell, E. M., O'Neill, G. A., & Aitken, S. N. (2012). Projecting future distributions of ecosystem climate niches: Uncertainties and management applications. *Forest Ecology and Management*, *279*, 128–140. https://doi.org/10.1016/j.foreco.2012.05.034

Westley, F., Olsson, P., Folke, C., Homer-Dixon, T., Vredenburg, H., Loorbach, D., Thompson, J., Nilsson, M., Lambin, E., Sendzimir, J., Banerjee, B., Galaz, V., & van der Leeuw, S. (2011). Tipping toward sustainability: Emerging pathways of transformation. *Ambio*, *40*(7), 762–780. https://doi.org/10.1007/s13280-011-0186-9

Weyant, J., Davidson, O., Dowlatabadi, H., Edmonds, J., Grubb, M., Parson, E. A., Richels, R., Rotmans, J., Shukla, P., Tol, R. S. J., Cline, W., & Fankhauser, S. (1996). Integrated assessment of climate change: An overview and comparison of approaches and results. In J. P. Bruce, H. L. Haites, & E. F. Haites (Eds.), *Economic and Social Dimensions of Climate Change* (pp. 371–393). IPCC, Cambridge University Press.

Whiting, J., Bleich, R., Vernon, T., Bowyer, T., & Larsen, R. (2012). WATER AVAILABILITY AND BIGHORN SHEEP: LIFE-HISTORY CHARACTERISTICS AND PERSISTENCE OF POPULATIONS. In J. A. Daniels (Ed.), *Advances in Environmental Research.* Nova Science Publishers, Inc.

Wiek, A., Withycombe, L., & Redman, C. L. (2011). Key competencies in sustainability: A reference framework for academic program development. *Sustainability Science*, *6*(2), 203–218. https://doi.org/10.1007/s11625-011-0132-6

Wilder, B. T., Betancourt, J. L., Epps, C. W., Crowhurst, R. S., Mead, J. I., & Ezcurra, E. (2014). Local extinction and unintentional rewilding of bighorn sheep (Ovis canadensis) on a Desert Island. *PLoS ONE*, *9*(3). https://doi.org/10.1371/journal.pone.0091358

Williams, B. K., & Brown, E. D. (2014). Adaptive management: From more talk to real action. *Environmental Management*, *53*(2), 465–479. https://doi.org/10.1007/s00267-013-0205-7

Williams, B. K., & Brown, E. D. (2016). Technical challenges in the application of adaptive management. *Biological Conservation*, *195*, 255–263. https://doi.org/10.1016/j.biocon.2016.01.012

Zhong, L., Ma, Y., & Salama, M. S. (2010). Assessment of vegetation dynamics and their response to variations in precipitation and temperature in the Tibetan Plateau. *Climatic Change*, *103*, 519–535.