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EVALUACIÓN DE LA RESILIENCIA DE LOS PETENES EN MÉXICO AL AUMENTO DEL NIVEL DEL MAR POR EL CAMBIO CLIMÁTICO

TESIS

Presentado como requisito parcial para optar al grado de Maestría en Ciencias en Recursos Naturales y Desarrollo Rural

Presentada por:

Mariana C. Hernández-Montilla

2015

DEDICATORIA Y AGRADECIMIENTOS

A mi madre siempre alegre y optimista y a mi Canito, ¡los amo tantísimo!

Gracias a todas las personas e instituciones que aportaron su apoyo y conocimiento en mi proceso formativo contribuyendo de manera significativa en el alcance de esta meta, tanto a los mencionados y no mencionados en esta página, pero que de una u otra forma les he expresado mi gratitud por el apoyo incondicional.

Primeramente agradezco enormemente al Dr. Miguel Ángel Martínez por abrirme las puertas de México y confiar en mí hasta el último momento, además de su paciencia, apoyo, tiempo y sugerencias que hicieron posible la realización de esta investigación y mi crecimiento personal y profesional.

Esta meta además no sería posible sin el asesoramiento del Dr. Ben de Jong y el Dr. Gregorio Posada así como todos los miembros del Comité Tutelar a quienes les agradezco profundamente los consejos y tiempo brindado de manera constante en el desarrollo de esta maestría.

Doy gracias de manera muy especial al Dr. Matt Hansen y a su equipo de investigación (Department of Geographical Sciences, University of Maryland) por haberme dado la oportunidad de compartir su tiempo y experticia conmigo durante la trayectoria de esta investigación. Reconozco además con mucha gratitud el apoyo invaluable de mis colegas y amigos de Pronatura Mérida, Instituto Geográfico Agustín Codazzi (IGAC), Centro de Investigación Científica de Yucatán (CICY Mérida), Placer County Water Agency (PCWA), The Nature Conservancy (TNC) y el Instituto Venezolano de Investigaciones Científicas (IVIC), así como a los profesores y personal técnico y administrativo del Colegio de la Frontera Sur (ECOSUR), quienes siempre estuvieron dispuestos a contribuir.

Agradezco además a los compañeros y compañeras que compartieron este desafiante tiempo conmigo y aún más, a todos aquellos que llegaron a convertirse en amistades y alianzas incondicionales, que hicieron de esta etapa, la mejor de mi vida.

Finalmente, agradezco al Consejo Nacional de Ciencia y Tecnología (CONACYT) y a ECOSUR, por las becas otorgadas y el apoyo financiero para la realización de mis estudios de maestría, los cuales me permitieron abrirme camino en este hermoso país.

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RESUMEN

Evaluación de la resiliencia de los petenes en México al aumento del nivel del mar por el cambio climático.

Mariana C Hernández-Montilla.1; Martínez Morales, Miguel Angel1; Bernardus H. J. de Jong1; Gregorio Posada-Vanegas.

1. El Colegio de la Frontera Sur, Campeche
2. EPOMEX

(mhernandez@ecosur.edu.mx, mmartinez@ecosur.mx, bjong@ecosur.mx, gposadav@uacam.mx)

Existe una necesidad creciente de evaluar la resiliencia de las zonas costeras en México a las futuras perturbaciones climáticas y de comprender sus procesos subyacentes con el fin de formular estrategias de respuesta más apropiadas. En este estudio se propone que es posible evaluar la capacidad de resiliencia de los ecosistemas costeros al aumento del nivel del mar debido al cambio climático tomando como base los Petenes ubicados en la Reserva de Biósfera Los Petenes en la Península de Yucatán, México. Con este fin, se diseñó un método de análisis multicriterio donde se ponderaron cuantitavemente indicadores de vulnerabilidad y persistencia para entender el impacto (exposición al riesgo) de un fenómeno meteorológico concreto, “aumento del nivel del mar”, y su respuesta (sensibilidad) a este evento. Estos indicadores y sus criterios se integraron en una matriz compleja para explicar la resiliencia espacial y temporal de los petenes al cambio climático. Esta investigación reveló que el 18,5% del área de estudio es altamente resiliente, mientras que el 38,6% tiene baja resiliencia. Las zonas resilientes más significativas se encontraron alejadas de la zona costera, con la influencia indirecta de las mareas y consistió principalmente en zonas con petenes rodeados de manglares de cuenca y bosque inundables. Este estudio demostró que el análisis multi-criterio y el uso de los SIG para el análisis espacial cualitativo, semi-cuantitativo y estadístico son una poderosa herramienta para derivar mapas ecológicos de resiliencia de los ecosistemas costeros que son altamente vulnerables al aumento del nivel del mar. Éste método podría ser utilizado en otros sitios de México y otros países, para el análisis y toma de decisiones relacionados a los procesos de gestión y conservación de las zonas costeras.

Palabras clave: Petenes, resiliencia, aumento del nivel del mar, cambio climático.

CAPÍTULO I

I. INTRODUCCIÓN

La evaluación de resiliencia de las zonas costeras en México a las futuras perturbaciones climáticas con frecuencia se ve obstaculizada por la disponibilidad de los recursos necesarios. Esto podría dificultar la aplicación de estrategias de conservación efectivas en estos ambientes vulnerables.

Los ecosistemas costeros son sistemas dinámicos y complejos caracterizados por su alta productividad que se encuentran expuestos a una amplia variedad de factores de estrés humanos y naturales (Nicholls et al., 2007). Una literatura extensa y creciente demuestra los grandes impactos potenciales del aumento del nivel del mar (ANM) y la evidencia científica es ahora abrumadora (Harvey and Nicholls, 2008; Nicholls, 2011). Dasgupta (2008), afirma que la formación de tormentas más intensas, el aumento de las temperaturas superficiales del mar, las variaciones del oleaje y las características de escorrentía contribuirán al incremento del nivel del mar e intensificarán los riesgos. Por lo tanto, el ANM debido al cambio climático representa una carga adicional que puede introducir aún más vulnerabilidad a los ecosistemas costeros amenazando su resiliencia (Kennedy et al., 2002; Ramieri et al., 2011).

Desde el último informe del IPCC (AR5) en el 2013, los sesgos instrumentales en los registros de temperatura superior del océano se han identificado y reducido, mejorando la confianza en la evaluación del ANM y arrojando resultados con una confianza muy alta

(IPCC, 2013). El IPCC en su último informe estima un ANM de 82 cm para el año 2100. No obstante, estimaciones más altas, arrojan un estimado de ANM de 190 cm con una probabilidad del 5% para el escenario RCP8.5 en el mencionado informe. Paralelamente, Grinsted y colaboradores (2009) han realizado investigaciones utilizando datos paleoclimáticos, estas muestran que el océano podría aumentar en los próximos 100 años un metro por encima del nivel medio actual del mar. Hasta la fecha las estimaciones oficiales, fueron publicadas por el IPCC en el año 2009 registrando un intervalo que va desde 0.5 hasta 2.0 m de ANM para el año 2100 (IPCC-AR4, 2009) (Nerheim, 2008).

México no escapa del cambio climático y sus efectos, sin embargo los estudios regionales dedicados a abordar las consecuencias de los escenarios de ANM en los ecosistemas costeros, son todavía escasos y las incertidumbres abundan. De acuerdo con la tercera Comunicación Nacional ante la Convención Marco de las Naciones Unidas sobre Cambio Climático del 2006, se espera que el clima de México sea más cálido para el 2020, 2050 y 2080, principalmente en los estados del norte del país, donde la temperatura puede aumentar entre 2 y 4ºC; mientras tanto, la temperatura de la superficie del mar en el Caribe, Golfo de México y Pacífico Mexicano, podría aumentar entre 1 y 1.5°C (INE, 2006). Éste calentamiento significaría una posible subida del nivel del mar de entre 20 y 165 cm, así como cambios en los patrones de lluvias, huracanes y tormentas, lo que inundaría por completo muchas ciudades y zonas costeras del país (Espadas et al., 2009).

Al respecto, Ortiz y Méndez (1999) mencionan que al aumentar el nivel del mar de 1 a 2 m en el Golfo de México, los estados y las zonas costeras que se consideran más vulnerables a los efectos del cambio climático son: Tamaulipas (desembocadura del río Bravo), Veracruz (Laguna de Alvarado, río Papaloapan), Tabasco (complejo deltaico Grijalva-Mezcapala-Usumacinta), y la Península de Yucatán, (en particular, los petenes de Campeche-Yucatán); lugares donde el agua podría introducirse hasta 40 km tierra dentro (Conde, 2007).

En consecuencia, el ANM, podría causar grandes trastornos a los ecosistemas costeros y particularmente, los petenes será uno de los más frente a los efectos del incremento del nivel del mar, fuerza de vientos, oleaje, corrientes y patrón de tormentas (Sánchez, Yañez-Arancibia, Ramírez-Gordillo and Day, Templet, 2004). La vulnerabilidad de los petenes, hace propicia la presente investigación. El área de estudio fue la Reserva de Biósfera Los Petenes (RBLP) por su predominante presencia de dicho ecosistema. Ésta se localiza al Sureste de la República Mexicana, específicamente al Noroeste de la península de Yucatán abarcando la costa Norte del Estado de Campeche. Representa una larga y estrecha franja costera que cubre una superficie de 282,858 has, diferenciándose dos zonas; la terrestre con 100,939 has y la marina con 181,919 has (Figura 1).

La RBLP cuenta con al menos 678 especies de plantas superiores, de 103 familias y 404 géneros, incluye 24 especies endémicas de la península de Yucatán, tres amenazadas (NOM-059-SEMARNAT-2001) y cinco sujetas a protección especial (Durán Garcia, 1995; Yañez-Arancibia, 2010). El paisaje de la reserva está formado por diferentes ecosistemas o humedales como manglares en sus diferentes modalidades (Yánez-Arancibia et al., 1996), zacatales representados por comunidades de tulares, chechenales, selva baja subperennifolia (inundable) y los petenes (CONANP-SEMARNAT, 2006).

La característica más notable de la RBLP, es la presencia de petenes, estas asociaciones vegetales se caracterizan por ser islas de vegetación arbolada (manglar o selva) de forma circular inmersas en una matriz de vegetación herbácea, de manglar disperso o de selva estructuralmente más baja perennifolia y subperennifolia en zonas inundables cuya altura va de los 8 hasta los 25 m de altura (Herrera-Silveira, Ciau-Cardozo, Toyohiko and Tsuruda, 2010).

Este ecosistema yace en una planicie costera con inclinaciones del terreno menores a 5% y una altitud promedio de 15 msnm lo que lo hace propicio a inundaciones perennes, semipermanentes y estacionales (Torrescano-Valle & Islebe 2012). Se caracterizan por poseer suelos de origen orgánico, oscuros, delgados (0-20cm) y predominantemente kársticos con escurrimientos hídricos superficiales escasos y un flujo hídrico subterráneo que conecta entre sí a los petenes con la tierra firme y el mar y que en ocasiones disuelve las calizas superficiales dando lugar a los cenotes (Rico-Gray and Palacios, 1996; Bautista and Palacio, 2005; CONANP-SEMARNAT, 2006).

Además, se encuentran asociados a un afloramiento de agua dulce el cual le proporciona a la vegetación, el agua suficiente para soportar la larga sequía y poseer la condición perennifolia o subperennifolia (Rico-Gray, 1982; Olmsted and Durán, 1988; CONANP-SEMARNAT, 2006). Las condiciones orográficas de la región y la vecindad con el

Golfo de México, determinan el clima que predomina en la RBLP, resultando en un clima cálido y húmedo con lluvias en verano (Aw) en la zona Centro-Sur de la RBLP y semiseco y seco cálido (BS'h'w) en su extremo Norte; una temperatura media anual, que varía de 27.8 °C en el Norte a 26.4 °C en el Sur y una precipitación media anual que va de 725.5 a 1049.7 mm respectivamente (CONANP-SEMARNAT, 2006).

Los principales fenómenos meteorológicos que afectan periódicamente a la Península de Yucatán y en consecuencia a la RBLP, están relacionados con la época climática del año (junio-octubre, durante la época de secas "verano" se presenta la temporada de lluvias y la sequía intraestival llamada canícula, la cual se distingue por sus altas temperaturas continuas); (noviembre-enero, se presenta la temporada de "invierno", en ésta no hay presencia de heladas y en cuanto a huracanes, su litoral es el de menor incidencia en toda la Península). Durante todo el año se pueden observar los frentes fríos (nortes) que afectan temporalmente el clima de la región (CONANP-SEMARNAT, 2006; CONAGUA, 2008). No obstante, la principal amenaza de los petenes, por su localización en la zona intermareal, es la intrusión de agua salina en los acuíferos de agua dulce, siendo las mareas determinantes en las interacciones físicas y biológicas que ocurren entre la plataforma continental adyacente y las tierras bajas de la RBLP (Grivel-Piña, 1992).

El promedio de mareas en la Reserva es de 0.6 m y representa uno de los principales mecanismos de aporte de agua salada, además la baja pendiente en la plataforma continental y los fuertes vientos que acompañan a los nortes, favorecen las inundaciones constantes, principalmente durante el otoño e invierno (CONANP-SEMARNAT, 2006).

No obstante, a pesar de la vulnerabilidad de este importante ecosistema costero, hasta la fecha no se han realizado estudios regionales de análisis de vulnerabilidad ni resiliencia y no se cuenta con información satelital digital de alta resolución disponible que permita diseñar estrategias de conservación con datos precisos.

Hace tan sólo cuatro décadas, se introdujo el término resiliencia en la literatura ecológica por el ecólogo teórico C.S. Holling como una manera de ayudar a comprender las dinámicas no lineales observadas en los ecosistemas perturbados, centrándose en la persistencia de las poblaciones o comunidades a nivel de ecosistemas (Brand and Jax, 2007). Holling, definió la resiliencia ecológica como la cantidad de perturbación que un ecosistema puede soportar sin cambiar sus procesos, organización y estructura (Holling, 1973) y desde entonces, múltiples significados del concepto han aparecido dando al concepto de resiliencia una rica historia, a veces con modificaciones considerables de su significado original (Gallopín, 2006; Folke, 2006). No obstante, estos múltiples significados están relacionados con supuestos sobre la presencia de equilibrios ya sea individuales o múltiples en un sistema (Holling, 1996). Por ejemplo, Begón definió la resiliencia como el tiempo necesario para volver a un estado estable después de una perturbación (Begon et al, 1996). En esta definición de resiliencia, se encuentra implícito el hecho de que existe un punto único de equilibrio. De ahí que la resiliencia se mide como como la distancia en la que el sistema se ha movido del punto de equilibrio (en el tiempo) y la velocidad con la que regresa a su condición estable (Gunderson, 2000).

Otros autores consideran la resiliencia como la magnitud de perturbación que puede ser absorbida por el sistema antes de que este cambie su estructura, variables y procesos que controlan el comportamiento del mismo (Gunderson et al., 2002) o la capacidad de un sistema para experimentar diferentes perturbaciones mientras que conserva esencialmente su función, estructura, retroalimentación, y capacidad de identidad (Walker et al., 2002; Walker, Holling, Carpenter and Kinzig, 2004; Walker et al., 2006). Este segundo tipo de resiliencia hace hincapié en un sistema con múltiples condiciones de equilibrio o dominios de estabilidad (Holling, 1973; Gunderson, 2000). Reconociendo que los ecosistemas presentan múltiples equilibrios, las teorías de resiliencia actuales prevén los ecosistemas como en constante cambio (Turner et al. 2003).

Según Carpenter (2001), el primer paso para hacer operativa la resiliencia es aplicar este término a casos empíricos así como también definir y especificar el objeto de estudio (Resilience of what to what?). Por lo tanto, no hay definiciones universalmente acordadas para el término dado, sino más bien las definiciones que sean apropiados para un objetivo determinado dentro de un sistema complejo (Brand and Jax, 2007).

En la presente investigación, el concepto de resiliencia ecológica supone la existencia de múltiples dominios de estabilidad definidos por la magnitud de la perturbación que el ecosistema puede absorber antes de cambiar sus estados estables o perder su tolerancia (Holling 1973; Holling 1996; Ludwig et al. 1997). Es importante tener en cuenta desde el principio, que este estudio tiene que ver con la capacidad de resiliencia del ecosistema de petenes y, aunque es difícil de medir in situ, esta capacidad es un atributo de los ecosistemas que puede ser fácilmente derivada a través de modelos de sistemas simples (DeAngelis, 1992). Aunque muchos aspectos de los ecosistemas se simplifican o idealizan cuando formulamos modelos, y no podemos esperar que un modelo simple simule todas las complejidades de los ecosistemas reales (Cropp and Gabric, 2002), estos modelos pueden conducir a una comprensión más profunda del fenómeno modelado incluso cuando varias teorías podrían ser necesarias a fin de explicar ciertos procesos que ayuden en la toma de decisiones (Bazykin, Khibnik and Krauskopf, 1998; Paine, 2002). Por ejemplo, aunque un análisis exhaustivo de resiliencia ecológica idealmente consideraría la totalidad del sistema, este ideal no es realista. Sin embargo, todos los procesos que se producen en un ecosistema determinado son el resultado de distintas clases de causas funcionales y evolutivas.

Tomando en consideración lo mencionado anteriormente, en la presente investigación partimos del marco del análisis de vulnerabilidad diseñado por Turner y colaboradores (2003) denominado modelo de riesgo-amenaza (*Risk-Hazard model* (RH) (Figura 2) el cual podría ayudarnos a entender el impacto de un evento en particular al riesgo (ANM) y su respuesta (sensibilidad) a la entidad expuesta (Kates, 1985). Este modelo fue desarrollado por el Programa de investigación y de evaluación de la Sustentabilidad (http://sust.harvard.edu) con el objeto de realizar análisis de vulnerabilidad en consonancia con las preocupaciones de la sostenibilidad y la ciencia del cambio ambiental global (Turner et al., 2003). Cabe destacar que las aplicaciones anteriores de este modelo cuantitativo en evaluaciones ambientales y climáticas, generalmente enfatizaban la exposición y la sensibilidad al riesgo a los factores de estrés (Warrick, 1980; Riebsame, 1991 citados por (Turner et al., 2003). Sin embargo, con el propósito de este estudio, se consideró el indicador "persistencia" del sistema ecológico a través del tiempo en el modelo utilizado, basado en el linaje de la resiliencia ecológica y delimitado en la idea central de distintos dominios de estabilidad (Figura 3). Persistencia, representa una propiedad fundamental del concepto de estabilidad que corresponde a ecosistemas, por lo tanto, es un concepto integral y cualitativo de la resiliencia (Brand, 2005).

El modelo RH de Turner se caracteriza por su enfoque basado en indicadores que se han utilizado anteriormente para caracterizar asuntos costeros clave así como también el estado actual de los ecosistemas costeros, sus presiones, impactos humanos, exposición, sensibilidad y riesgo (Ramieri et al., 2011). Estos indicadores (exposición, sensibilidad y persistencia) fueron utilizados en este estudio para desarrollar una matriz simple, basada en medidas y métricas con conexiones que operan a diferentes escalas espacio-temporales que involucraron procesos estocásticos y no lineales. Este procedimiento nos permitió formular un sistema de criterios cuantitativos y cualitativos que reflejaron diferentes aspectos de la vulnerabilidad y la resiliencia asumiendo la persistencia del ecosistema a través del tiempo y la existencia de múltiples dominios de estabilidad (Ludwig, Walker and Holling, 1997; Gunderson and Holling, 2002).

Asumimos entonces que un ecosistema altamente resiliente presentaría una baja exposición y sensibilidad al riesgo. Siendo entonces la exposición una variable directamente proporcional a la sensibilidad y estos a su vez, inversamente proporcional a su persistencia.

Aunque se trata de un método experimental aplicado a sistemas dinámicos y no lineales, los resultados de esta investigación son sin embargo de importancia general para entender la resiliencia de los ecosistemas costeros (Figura 4).

Hemos aplicado este modelo de análisis de resiliencia en el ecosistema de petenes, en el supuesto de que es muy probable que la tasa de ANM media global impactará de forma negativa los sistemas costeros y las zonas bajas con impactos tales como inmersión, inundaciones y erosión costera (90-100% de probabilidad) (Seneviratne et al., 2012; IPCC, 2013). En respuesta a esta situación, el propósito principal de este estudio fue determinar las zonas más resilientes al ANM en la RBLP.

CAPÍTULO II.

Assessment of Hammocks (Petenes) Resilience to Sea Level Rise Due to Climate Change in Mexico

Mariana C. Hernández-Montilla[1¶*], Miguel Angel Martínez-Morales[1¶]; Gregorio Posada Vanegas[2&], Bernardus H. J. de Jong[3&]

[1] Departamento de Conservación de la Biodiversidad, El Colegio de la Frontera Sur, Campeche, Campeche, México. [2] Instituto de Ecología, Pesquerías y Oceanografía del Golfo de México, Universidad Autónoma de Campeche, Campeche, Campeche, México. [3] Departamento de Ciencias de la Sustentabilidad, El Colegio de la Frontera Sur, Campeche, Campeche, México.

*** Corresponding author:** (MCHM)

[¶] These authors contributed equally to this work

[&] These authors also contributed equally to this work.

Abstract

There is a pressing need to assess resilience of coastal ecosystems against sea level rise. The estimation of the magnitude of such future climate disturbance that these ecosystems can absorb and a better understanding of the underlying processes can be used to propose appropriate response strategies. Here, we propose that it is possible to assess resilience of hammocks, a highly vulnerable ecosystem, against sea level rise due to climate change, even with a lack of high-precision data. We built resilience models by incorporating and weighting appropriate indicators of persistence criteria to assess hammock resilience against flooding due to climate-change at “Los Petenes Biosphere Reserve”, in the Yucatan Peninsula, Mexico. We describe and assess the approaches and methods used to derive ecological resilience maps of coastal ecosystems that are highly vulnerable to sea level rise due to climate change. Our research highlighted that 18.5% of the study area is highly resilient (hotspot), whereas 38.6% has low resilience (cold spot). The most significant hotspot clusters of resilience are located in areas distant to the coastal zone, with indirect tidal influence, and consisted mostly of hammocks surrounded by basin mangrove and floodplain forest. This study revealed that multi-criteria analysis and the use of GIS for qualitative, semi-quantitative and statistical spatial analysis are a powerful tool to derive ecological resilience maps of coastal ecosystems that are highly vulnerable to sea level rise. This method could be used in other sites of Mexico and other countries, to help develop resilience analysis and decision-making processes for management and conservation of coastal areas in a changing world.

Introduction

Coastal ecosystems are dynamic and complex systems that provide a wide array of goods and services, and are characterized for their remarkable biological productivity [1,2]. They are located at the interface between the terrestrial and marine environments and are generally exposed to a wide variety of environmental and human stressors [3]. The main natural impacts in these zones are related to sea-level rise (SLR) and other key meteorological phenomena, such as wind and storms. In addition, the burden of climate change may introduce further vulnerability and degrade these valuable ecosystems, threatening their resilience [4,5]. Persistence of coastal ecosystems are determined by the ability of the system to cope totally or partially with SLR by growing vertically, migrating inland or expanding laterally [6].

Four decades ago, the term *resilience* was introduced to the ecological literature by the theoretical ecologist C. S. Holling as a way of helping to understand the non-linear dynamics observed in disturbed ecosystems by focusing on the persistence of populations or communities at the ecosystem level [7]. He defined ecological resilience as the amount of disturbance that an ecosystem could withstand without changing self-organized processes and structures [8]. Since then, multiple meanings of the concept have appeared giving to the concept of resilience a rich history, sometimes with a considerable stretch from its original meaning [9,10].

Recognizing that ecosystems often exhibit non- and multi-equilibria dynamics, current resilience theories envision ecosystems as constantly changing [11]. In terms of the stability of landscapes, the resilience implies the ability of a multi-stable system to keep the values of its state variables within a given domain of attraction in the face of perturbations, and is not concerned with the stability or constancy of the state within the basin. This concept is called ecological resilience [9,10].

The first step to make resilience operational is to apply this term to empirical cases because it is critical to make the definition practical and specify resilience of "what to what” [12]. Hence, there are no universally agreed definitions, but rather definitions that are appropriate for a certain objective within a complex system [7]. Adopting usual conventions, in this research the concept of ecological resilience assumes the existence of multiple stability domains defined by the magnitude of disturbance that the ecosystem can absorb before it changes the stable states and the tolerance of the system to perturbations [13,14].

Vulnerability analyses could help us to understand the impact of a particular hazard event such as the SLR and the dose-response of the entity exposed [15]. So we started from the framework of vulnerability analysis applying the Risk Hazard model (RH) [11]. This model was developed to make vulnerability analysis consistent with the concerns of sustainability and global environmental change science [11]. Past quantitative applications of this model in environmental and climate impact assessment, generally emphasized exposure and sensitivity to perturbations and stressors. In this study, we proposed to include persistence of the ecological system based on the ecological resilience lineage and delimited from the core idea of multiple stability domains. Persistence represents a fundamental property of the stability concept that corresponds to whole ecosystems, therefore, it is a holistic and qualitative concept of resilience [16]. We used exposure, sensitivity and persistence to build a model to operationalize the resilience analysis based on the modified framework of the RH model [11]. So, a highly resilient ecosystem would present a lower exposure to risk and a lower sensitivity to stressors, and thus a higher persistence. Exposure to risk is therefore proportional to sensitivity and both are the inverse of persistence. Although this is a method applied to a particular dynamic and nonlinear system (the hammocks), it is of general relevance and useful for directing ideas to the understanding of the resilience of coastal ecosystems.

The method uses an indicator-based approach that has been used before to characterize aspects or the state of coastal ecosystems such as coastal drivers, pressures, human impacts, exposure, sensitivity, and risk to evaluate coastal vulnerability [5]. We developed a matrix based on basic measures and metrics of hammock exposure and sensitivity to SLR due to climate change at different spatiotemporal scales and commonly involving stochastic and nonlinear processes. We assume that it is very likely that the rate of global mean SLR will contribute to an upward trend in extreme coastal high water levels in throughout the 21st century. Coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal flooding, and coastal erosion [17,18].

Since coastal ecosystems like hammocks are particularly sensitive to coastal changes, the sole impact of climate change is difficult to assess given other drivers, particularly human-related (e.g., land-use change, coastal development, pollution) [19]. The main threat to hammocks is the intrusion of saltwater into their freshwater aquifer due to climate change, particularly by SLR [20]. The Convention on Biological Diversity (CBD) encouraged the development of tools and methods to aid countries to evaluate climate impacts and increase resilience of their protected area systems by focusing on the mitigation and adaptation of vulnerable ecosystems [21]. Ecosystems and species in protected areas will not be exempt from adverse effects [22]; therefore, we assessed the resilience of hammocks to SLR due to climate change in the natural protected area "Los Petenes Biosphere Reserve" (LPBR) in the Yucatan Peninsula, Mexico.

Methods

Los Petenes Biosphere Reserve (LPBR)

The LPBR is located in the north-western part of the Yucatan Peninsula (19°49'00''N to 20°51'30''; 90°20'00''W to 90°45'15'') (Fig. 1). This natural protected area represents a long, narrow coastal strip covering an area of 2,828.6 km^2, and comprises two zones: a land area of 1,009.4 km^2 and a marine area of 1,819.2 km^2. Its vegetation is characterized by hammocks forest (basin and fringe), mangrove forest (dwarf and hammocks), coastal dune scrub communities, flooded grassland, deciduous forest, floodplain forest, and lowland deciduous forest [23,24].

Fig. 1. Location of Los Petenes Biosphere Reserve in the Yucatan Peninsula, Mexico.

Hammock ecosystems are plant associations linked to spring water holes in predominantly karstic soils. They stand out by the vigour, height, and diversity of plant components in coastal wetland regions. Its importance lies in its wide diversity of flora and fauna and its intense dynamics with the sea by underground drainage [25]. Hammocks are ecosystems that are considered unique in the world because of their limited spatial distribution. These ecosystems only occur in the Yucatan Peninsula in Mexico, the Florida Peninsula in the USA, and in Cuba [26].

All the field permits issued for conducting this research were obtained through the main authority responsible for this natural protected area, Cesar Uriel Romero Herrera (Director). We also confirm that our field studies did not involve endangered or protected species.

Data acquisition

We assembled different data sources as GIS layers including aerial photographs (scale 1:75,000, February, 1998) and multispectral and panchromatic SPOT images (2012) obtained from El Colegio de la Frontera Sur (ECOSUR); a digital elevation model (DEM) “NEXTMap World 30” derived from the SRTM v2.1 merged with Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) 30 m, and a 1 km GTOPO30 (global digital elevation model with a horizontal grid spacing of 30 arc seconds, approximately 1 km) adjusted using 25 cm vertical accuracy Light Detection and Ranging (LiDAR) [27,28].

The hydrological data and maps were based on the shuttle elevation derivatives at multiple scales "HydroSHEDS" from elevation data of the *Shuttle Radar Topography Mission (*SRTM*)* at 3 arc-second resolution [29]. We also used the Mexican national cartography on land use and vegetation (series V, scale 1:250,000) from the INEGI database (www.inegi.org.mx) [30] developed from the interpretation of multispectral SPOT images (2012 and 2013); shapefiles of rivers and water bodies made accessible to us by the Universidad Autónoma de Campeche, and the "hurricanes historical data V 4.0" in GIS formats from the National Oceanic and Atmospheric Administration (NOAA) at the International Best Track Archive for Climate Stewardship "IBTrACS" database (www.catalog.data.gov/dataset/ncdc-international-best-track-archive-for-climate-stewardship-ibtracs-project-version-3) [31]. The GIS analysis were performed using IDRISI Selva (Clark Labs, Worcester) and ArcMap 10.0 (ESRI, Redlands).

Resilience conceptual framework

There are different views and definitions of resilience, for the purpose of this study we developed a conceptual framework through a combination of literature review, attendance at meetings of practitioners in the field of vulnerability, adaptation, resilience, and natural hazards, and discussions with key individuals. This gave us a context within which we developed a set of indicators to assess criteria of hammock persistence to SLR due to climate change and thus, resilience of this ecosystem.

We adjusted the vulnerability analysis framework, specifically the RH model [11] that emphasizes exposure and sensitivity to perturbations and stressors, considering persistence as a quantitative concept of the ecological resilience. We developed a hierarchical model to analyse, measure and weight the main ecological indicators to assess the exposure and sensitivity criteria. The interaction of these criteria generated an index of persistence to determine the most resilient areas at the LPBR (Fig. 2).

Fig. 2. Flow chart of the methodology used to assess hammock resilience to sea level rise due to climate change and to predict the most resilient areas at Los Petenes Biosphere Reserve.

Criteria assessment

We defined exposure and sensitivity to perturbations and stressors as criteria of hammock resilience. We then defined a set of indicators to assess each criterion. A score from 1 to 3 was used to weight each indicator, where lower values represented less exposure or sensitivity. We delimited 425 hammock polygons in the LPBR by analysing SPOT multispectral and panchromatic images, aerial photographs, and land use and vegetation digital maps. We assess the indicators of both criteria on each of these polygons.

Exposure

We defined five indicators to assess this criterion:

1) Flooding risk in SLR scenarios

Due to the multiple uncertainties on SLR projections and based on the precautionary principle, we assessed this indicator using three SLR scenarios due to climate change in the region, in the next 100 years, based on the Intergovernmental Panel on Climate Change (IPCC) Fourth and Fifth Assessment Report (AR4, AR5) as well as other regional projections [32–35]. The first scenario assumes an increase from 0 to 1 m above current sea level (ACSL), a second scenario assumes an increase from 1 to 2 m ACSL, and a third assumes an increase from 2 to 3 m ACSL.

We used the DEM and the 425 hammock polygons to do a series of GIS analyses to assess this indicator. We reclassified the DEM adjusting the outliers and assigned elevation scores from 1 to 3, where 1 represented the values from 2 to 3 m above sea level (ASL), 2 from 1 to 2 m ASL and 3, from 0 to 1 m ASL. We masked values from -5 to 0 m below sea level, and >3 to 26 m ASL. We then overlaid the hammock polygons on the reclassified DEM to estimate the proportion of flooded area on each polygon in each of the three SLR scenarios. We assigned one of three risk categories to the polygons according to their proportion of flooded area: (1) from 0 to 30%, (2) from >30 to 60%, and (3) >60%.

2) Coastal flooding risk

We considered this indicator due to the intrinsic vulnerability of coastal zones to SLR. We defined three risk categories for this indicator based on the hydrologic conditioning, the sink identification layer from HydroSHEDS and the DEM “Nextmap World 30”. With this data, we delimited the lowest-lying area next to the coastline and the natural sinks or depressions obtaining three zones that represented different exposure scores to flooding risk. The most exposed zone was the lowest-lying area (-5 to 3 m ASL; score 3) characterized by jungle hammocks, located in the coastal line (<4 km from the coastline) and coastal lagoons [36]; on the contrary, the less exposed zone corresponded to the highest zones (>8 m ASL) and the areas farthest from the coastline (>6 km from the coastline), so the lowest value of exposure was assigned (score 1). Finally we assigned a score of 2 to the remaining areas.

We overlaid these three risk zones on the 425 hammocks layer to assign a value of risk to each hammock. Since some of the hammock polygons were intersected by two risk zones, we assigned a risk category to the polygon based on the larger area proportion and the neighbourhood indicator.

3) Proximity to rivers

Modelling the hydrodynamic flow of watercourses was difficult because of the lack of highly precise data and logistical constrains to make accurate measurements at the LPBR. Therefore, based on discussions with specialists, we proposed the creation of three distance buffers from rivers and streams (0-100, >100-500, >500 m). These buffers were overlaid on the 425 hammocks layer in order to assign a risk category to each polygon (from 0 to 3). Zero represented no intersection, (1) >500 m from rivers, (2) from >100 to 500 m, and (3) within 0 to 100 m from rivers. Again, when a polygon was intersected by more than one risk category, we assigned the category that occupied the largest area proportion in the polygon.

4) Hurricane impact

To assess this indicator we relied on previous information of hurricane occurrence in the region through the analysis of hurricane frequency, intensity, magnitude and probability of occurrence, as well as its relationship with terrain. First, we downloaded the hurricane historical data in GIS formats from the NOAA [31] using a buffer of 200 km in the study area. We retrieved 990 hurricane tracks over a period of 171 years (1842-2013). Then, we generated buffers for each hurricane track according to its category (Saffir-Simpson scale) and its inland effect [37,38]. According to its level of impact (tropical depression [TD], tropical storm [TS] and hurricanes [H] from 1 to 4), we determined the size of the buffer: TD 1.6 km, TS 3.2 km, H1 6.4 km, H2 9.7 km, H3 12.9 km, and H4 16.1 km.

We then overlaid the buffers layer and the hammocks layer obtaining a total of 485 tracks that directly hit the LPBR. We estimated hurricane frequency and intensity of each hammock polygon based on the number of times it was intersected by hurricane tracks and its type. We weighted each hammock by multiplying the frequency of each track that hit it by their level of intensity, then we summed the total to obtain a unique value for each polygon. These values were finally normalized from 1 to 3 in order to assign a risk category to each hammock polygon to rate the impact of hurricanes.

5) Land cover change

To assess this indicator, we discerned the differences in reflectance between forested and non-forested areas using four georeferenced and orthorectified cloud-free

Landsat scenes at 30 m resolution (February 1979, Landsat 2; April 1990, Landsat 4; March 2003, Landsat 7 and December 2014, Landsat 8. Path/Row: 21/46).

We used a combination of unsupervised classification methods to digitally classify the pixels in all four Landsat images. We used the Iterative Self-Organizing Data Analysis Technique (ISODATA) in Idrisi Selva 17.0 (Clark Labs, Worcester) to perform an unsupervised classification on the images, resulting in 50 clusters in each and 25 iterations. We identified six thematic classes that represented the types of land cover in the study area, excluding shadow and cloud cover. The land cover types were: (1) high and dense vegetation, a class whose pixels were very green with the highest NDVI values characterized by the homogeneity of forest cover, mainly hammocks and mangroves; (2) discontinuous secondary forest, a forested class with low-density whose mixed pixels are characterized by a variety of land cover types including hammocks, intervened vegetation, low mangroves, and secondary mixed forest with a high NDVI value; (3) bushes and shrubs whose pixels have a low to medium NDVI values; (4) coastal dune scrub communities, cattail, grass, and brush whose pixels have a low Normalized Difference Vegetation Index (NDVI); (5) bare soil or sparse vegetation and dry grass and (6) water.

Pixels that we could clearly identify as belonging to one of the six classes were extracted from the image to reduce spectral variability across the remaining pixels. Reflectance values corresponding to dense vegetation and exposed areas such as salt flats and crops were used to create spectral signatures for classes. We grouped the remaining pixels into the mixed class containing mangroves, secondary vegetation, and small-scale subsistence agriculture. This process was followed in each one of the Landsat scenes. We developed GIS-based spatial analyses that assigned pixels to the most likely thematic class based on their location to discriminate among similar informational classes and to avoid classification errors in established classes. No field data was available, so we collected reference data to validate map accuracy; for example, we used the national vegetation maps to discriminate among different types of forest and orthophotos to identify the agricultural class.

Then we performed the land conversion analysis with the module Land Change Modeler available in Idrisi Selva [39]. In our analysis we considered a number of predictors, including slope, distance to settlements, distance to roads, and distance to agriculture to calibrate the model. Here, we ignored transitions below 1 km^2 and we used cross classification to compare the transition between the four classified images. Next, we overlaid the land cover change information with the hammock polygons layer to assess the proportion of land cover change in each hammock.

We assigned scores to each polygon according to its transition categories from 1 to 3, where 1 represented recovery, 2 perturbation, and 3 the loss of native vegetation. The polygons that showed no transition were also represented with the value 1. Finally, a sum of the cover types was performed on each polygon and normalized with the aim of generating a single value from 1 to 3 in each hammock, Table 1.

Table 1. Transitions between the different categories using Land Change Modeler (LCM).

Recovery	Perturbation	Loss
5, 4, 3, 2 to 1	4 to 5	2 to 4, 5
4 to 3, 2, 1	3 to 4	1, 2, 3, to 5
3 to 2	2 to 3	1 to 4
	1 to 2, 3	

(1) High and dense vegetation characterized by the homogeneity of forest cover, mainly hammocks and mangroves; (2) discontinuous secondary forest characterized by a variety of land cover types including hammocks, intervened vegetation, low mangroves, and secondary mixed forest; (3) bushes and shrubs; (4) cattail, grass, and brush, and (5) bare soil or sparse vegetation and dry grass

Sensitivity

We defined sensitivity as the intrinsic potential of hammocks to be affected by SLR. To assess this criterion, we used satellite imagery to estimate hammock structural properties. We defined three indicators for this criterion:

1) Hammock canopy height

We used a calibrated high-resolution (30 m) void-filled surface elevation DSM to measure forest canopy height [40]. We overlaid the DSM and the hammock polygons layer to assign a score to polygons based on their canopy height. Mangrove hammock forest scored 1 (average height of about 15 m due to the high concentrations of nutrients, low salinity and soil with a thick layer of organic matter. They are associated to spring waterholes, *Rizophora mangle* and *Laguncularia racemosa* are the dominant species [36]). Medium height mixed forest scored 2 (heights between 3 and <15 m. Here we could find different communities such as deciduous forest, floodplain forest, and lowland deciduous forest among others [36]). Finally, dwarf mangrove forest scored 3 (average height between 1.5 and <3 m. These are characterized by conditions with limited nutrients in the sediment and high salinity. It is dominated by *Rizophora mangle* [36]). Some hammock polygons were intersected by two height categories, therefore the score assigned was based on the category with the larger cover proportion.

2) Type of hammock

We identified and delimitated three types of hammocks using the orthophotos and the hammock polygons layer: basin hammocks, mixed hammock, and fringe hammocks. We then rated the type of hammocks based on their intrinsic sensitivity to SLR, basin hammocks scored 1, mixed hammocks scored 2, and fringe hammocks scored 3.

Basin hammocks are located behind the coastline, the tidal influence is indirect and lower compared to the one in the fringe hammock. This community can be monospecific or mixed forests of *Avicennia germinans* if the salinity is high or Laguncularia racemosa if the salinity is relatively low [36]. On the other hand, fringe hammocks, are mainly located in the coastal line and coastal lagoons; they are daily influenced by the tide (semidiurnal, with 0.6m medium amplitude, [41]), so they are flooded and dried almost daily. They are also exposed to the winds and the dominant species is *Rizophora mangle* [36]. Some of the hammocks (mixed hammocks) could not be distinguished between basin and fringe hammocks; in this case, hammocks could be influenced both by winds and tides, but their impact is lower than in the fringe hammocks.

3) Patch size

The surface of a patch is perhaps the most important and useful element in the analysis of a landscape [42]. We used the hammock polygons layer to classify hammocks by their size. Hammock patches ranged from 0.15 to 89.6 km^2. Here we assume that larger patches are less sensitive to SLR; in contrast, smaller habitat patches are relatively less likely to rebound from disturbances (i.e., are more likely to be fragmented or destroyed after changes in hydrology, destruction of vegetation, or the establishment of opportunistic flora and fauna) than larger habitat patches [43], so, we defined three size categories. The largest larges patches (>5 to 89.6 km^2) got the lowest values of sensitivity (1), the smallest patches (>0.01 to <1.5 km^2) got the highest values of sensitivity (3) and finally, remaining patches (>1.5 to <5 km2) got a medium value of sensitivity (2).

Persistence

Persistence of coastal ecosystems is determined by the interaction of climate and anthropogenic factors [44]. Here we defined hammock persistence as the interaction between its exposure and sensitivity criteria. To assess persistence, we first weighted scores of all the indicators of each criterion multiplying the score by a value of importance, Table

2, based on the impact of the indicators in the flooding of hammocks and adjusted by the opinion of experts and published research (Fig. 3).

Fig. 3. Map of persistent areas at Los Petenes Biosphere Reserve.

Table 2. Weighting values applied to the scores of all the indicators of each criterion to assess the persistent index of hammocks.

Criteria	**Indicators**	**Weighting values**
Sensitivity	Height hammock	0.3
Sensitivity	Type of hammock	0.4
Sensitivity	Patch size	0.3
Exposure	Flooding risk in SLR scenarios	0.3
Exposure	Coastal flooding risk	0.2
Exposure	Proximity to rivers	0.2
Exposure	Hurricanes impact	0.1
Exposure	Land Cover Change	0.2

We estimated hammock persistence based on the following expression:

where,

P = index of *persistence*

E = the weighted value of each exposure indicator

S = the weighted value of each sensitivity indicator

Finally, we estimated the persistence value for each hammock polygon.

Delimitation of resilient areas

The persistence index (P) for each polygon was interpolated to delimit the resilient areas by Ordinary Kriging. We did this analysis to predict potential resilient areas to coastal flooding by SLR and to identify potential priority areas for conservation as well as areas where can be implemented mitigation plans. The Ordinary Kriging is one of the mostly used geo-statistical methods, quite efficient and accurate for spatial prediction and interpolation [45].

We used a spatial pattern detection technique to analyse clusters of high and low values of persistence. This analysis allowed that we could identify areas that experience a significantly higher level of persistence to coastal flooding due to SLR at the RBLP, and to assess that these values were not random events. We used the Getis–Ord G_i* statistic [46] to analyse resilience of hammocks at the LPBR.

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \overline{X} \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j} \right)^2 \right]}{n-1}}}$$

where,

$$\overline{X} = \frac{\sum_{j=1}^{n} x_j}{n} \qquad S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{X})^2}$$

This statistic provided a continuous variable measuring the cold spots or very low (-7.33 to -2.99 Gi* score) and low resilient areas (-2.99 to -0.96 G_i* score), as well as the moderate (-0.96 to 1.28 G_i* score), high (1.28 to 3.93 G_i* score), and very high (3-93 to 7.03 G_i* score) hotspots of resilience. In this sense, a low Gi* shows no pattern (a random distribution) and represents non-resilient areas, whereas a high Gi* shows clustered patterns and represents highly resilient areas.

We performed a sensitivity analysis to assess the sensitivity of the estimated hammock resilience to the choice of alternative weighting schemes. We assessed three indicator weighting schemes besides our baseline weighting, Table 3.

Table 3. Weighting schemes used to assess their effect on the estimated resilience of hammocks in the LPBR.

Criteria	Indicators	Baseline weighting	Scheme 1	Scheme 2	Scheme 3
Exposure	Flooding risk in SLR scenarios	0.3	0.2	0.2	0.2
Exposure	Coastal flooding risk	0.2	0.2	0.2	0.3
Exposure	Proximity to rivers	0.2	0.2	0.2	0.1
Exposure	Hurricane impacts	0.1	0.2	0.1	0.2
Exposure	Land cover change	0.2	0.2	0.3	0.2
Sensitivity	Hammock canopy height	0.3	0.3	0.4	0.3

Sensitivity	Type of hammock	0.4	0.3	0.3	0.3
Sensitivity	Patch size	0.3	0.3	0.3	0.4

Results

We found that 21.3 km^2 (2.1%) of the LPBR had very high resilience to SLR due to climate change, and 167.2 km^2 (16.4%) had high resilience (Fig. 4). These areas were characterized by being distant to the coastal zone, had an indirect tidal influence, and consisted of hammocks surrounded by basin mangrove and floodplain forest. These areas also had a low influence of rivers and channels, and a low probability of hurricane occurrence. These areas were located at the north-eastern and eastern portions of the LPBR. On the other hand, hammocks with very low resilience covered an area of 151.3 km^2 (14.9%) and hammocks with low resilience an area of 241.2 km^2 (23.7%). These hammocks were located in coastal areas without vegetation or with scattered mangroves, and with a direct influence of tides and winds. Areas with medium resilience had dense and high vegetation, they had a very low sensitivity, and high levels of exposure mainly because of a high rate of land cover change. These areas were located at the north-western and southern portions of the LPBR

Fig. 4. Map of resilient areas at Los Petenes Biosphere Reserve. (Red and orange colors represent hotspots areas and blue and light blue, the coldspots areas of resilience).

The assessment of the three other weighting schemes used to assess their effect on the estimated resilience of hammocks in the LPBR (Table 3), showed that high resilient areas had a coincidence of 73.9% with the scheme 1, 64.3% with the scheme 2, and 72.4% with the scheme 3. Since resilient indicators are quite controversial, we considered appropriate the weighting we gave to the criteria based on the opinion of experts, published research, and our results of the sensitivity analysis as well the data used for this research.

In the assessment of the criterion “exposure” we found that the highest proportion of the area was represented by the lowest risk category in the indicator “flooding risk in SLR scenarios” (95.1% low, 2.8% moderate and 2.1% high risk) and “land cover change” (47.6% low, 26.8% moderate and 25.6% high risk). However, in the indicators “coastal flooding risk” and “hurricane impact”, we obtained the highest proportion of the area under the category moderate risk (63.1%), followed by low (27.5%), and high (9.4%) for the “coastal flooding risk”, and moderate (53.0%), low (46.5%) and high (0.4%) for “hurricane impact”. Finally, in the indicator “proximity to rivers” 38.5% of the area of the polygons assessed belonged to the highest risk category, 25.1% to moderate, and 36.3% to low. Based on the interpolation of the indicators of “exposure”, we found that 16.7% of the study area presented very low exposure to risk, 28.1% low, 35.5% moderate, 13.8% high and 6.0% very high (Fig. 5).

Fig. 5. Map of exposure to risk at Los Petenes Biosphere Reserve.

In the assessment of the criterion “sensitivity” we found that the highest proportion of the area was represented by the moderate risk category in the indicators “hammock canopy height" (0.6% high, 94.6% moderate, and 4.8% low) and "type of hammock" (44.1% high, 46.7% moderate, and 9.2% low). In the indicator "patch size", the highest proportion corresponded to the category of risk high (49.4%) followed by low (41.9%), and moderate (8.7%). The interpolation of the indicators of "sensitivity" showed us that 22.6% of the study area presented very low sensitivity to risk, 34.6% low, 9.4% moderate, 15.3% high, and 18.0 very high (Fig. 6).

Fig. 6. Map of sensitivity areas at Los Petenes Biosphere Reserve.

Discussion

We developed a resilience index based on qualitative and quantitative data to assess the magnitude of estimated future disturbances on an ecosystem. This type of study would also allow a better design of response strategies to face disturbances on ecosystems based on the fact that hammocks are very sensitive to changes in SLR and an increase between 12 and 17 cm in 100 years could collapse these ecosystems [47,48].

While a comprehensive resilience analysis would ideally consider the entire ecosystem, this is unrealistic. Nevertheless, every process that occurs in a determined ecosystem is the result of distinct sorts of functional and evolutionary causes and many aspects of ecosystems are simplified or idealized when we formulate models [49]. Although simple models cannot simulate all the intricacies of real ecosystems, these can give us a deeper understanding of a modelled phenomenon even when several theories might be necessary to explain certain processes that aid in decision making [50,51].

We consider that both the criteria and indicators used in this research were appropriate. However, we are aware that coastal ecosystems are also particularly sensitive to other variables such as the increase in sea surface temperature, ocean acidification, salt water intrusion, rising water tables, and to altered runoff patterns [5].

Hammock persistence could also be affected by rainfall patterns because precipitation and water seep into the ground water table tend to dissolve the limestone surface (karst) causing the formation of sinkholes and then of hammocks. Although we could not assess the rate (not to mention the change in rate) of hammock formation due to changes in precipitation patterns due to climate change, this is for sure a variable that remains to be analysed. The Mexican state of Campeche is located in one of the most vulnerable regions subjected to drought, and this tends to worsen [52,53]. The assessment of precipitation averages projected to 100 years (1980-1999 to 2080-2099) in the Fourth Report on Climate Change of the Intergovernmental Panel on Climate Change [33], indicate a decrease in annual precipitation for the entire Central American region. In other study in the Yucatan Peninsula, researchers estimated a decrease in annual precipitation from 10 to 15% and over 30% in the dry and rainy seasons respectively [52,53]. Similarly, Magrin et al. [54], also estimated a decrease between 10 to 22% in annual precipitation by 2090, with periods of drought which could reach up to a reduction of 48%. This decrease in rainfall could cause more intense droughts and more frequent forest fires [55] which would further threaten hammocks resilience.

Proximity to coastline, though important to define hammock resilience, is just one of the several factors that determine resilience. For example, coastal areas at the LPBR are structured by an array of parallel stripes to the coastline due to the presence of fringe mangrove that grow in marine waters where beaches are not present along the coast. This suggests a low physical energy from the environment, allowing mangroves to trap sediments and litter [32]. This process raises banks in the coast and estuaries, reducing hammock exposure, as it occurs in the LPBR and adjacent areas (Celestún and Isla Arena).

On the other hand, it is important to mention that we used spatial statistical techniques to analyse the data. Our primary reason was to incorporate the relationships between adjacent areas by spatial autocorrelation in order to add significance to the resilient areas. Based in our results we consider that Getis–Ord Gi* statistic was appropriate to analyse the resilience of hammocks at the LPBR [46].

Although the LPBR is a natural protected area, we found that the rate of land cover change in some areas is high, particularly those areas with dense and high vegetation out of the core areas of the LPBR. Land cover change due to human activities could significantly compromise the potential of inland hammock migration due to SLR as salt water intrudes the coastline.

The fact that the surface of the LPBR has been decreed as a natural protected area, do not necessarily grants its conservation effectiveness in a changing world. This proposed methodological framework to assess resilience due to climate change has proved to be efficient when high-precision data is missing. This is a fairly common situation in many studies, and in countries such as Mexico, where high-precision eco-geographical data is still being produced.

Resilience analysis in highly vulnerable ecosystems such as hammocks are urgently needed because decisions have to be taken based on the best available information to implement the most appropriate adaptation or mitigation strategy so we expect that our research can contribute to this purpose.

Acknowledgments

We thank to the Laboratorio de Análisis de Información Geográfica y Estadística (LAIGE-ECOSUR), the Instituto Nacional de Estadística y Geografía (INEGI) and Intermap Technologies, for providing the digital data used in this study. We also thank to the Department of Geographical Sciences at the University of Maryland, Pronatura, and the Centro de Investigación Científica de Yucatán (CICY) for providing technical consultancies, reviews and office space during the development of this research. We are also very grateful to the reviewers for their valuable comments and their support in the analysis of the data.

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CAPÍTULO III.

I. CONCLUSIONES

Elaboramos un índice resiliencia basado en datos cualitativos y cuantitativos para evaluar el impacto del aumento del nivel del mar (ANM) por el cambio climático en el ecosistema de petenes en la Reserva de Biósfera Los Petenes (RBLP) en la Península de Yucatán, México.

Encontramos que menos del 20% del área evaluada tenía una alta capacidad de resiliencia. Estas áreas se caracterizaron por ser distantes a la zona costera, con una influencia indirecta de mareas, bosques densos y una baja probabilidad de ocurrencia de huracanes. Por otro lado, los petenes con baja resiliencia cubrieron aproximadamente un 40% del área de estudio y se caracterizó por su ubicación en la franja costera, su escasa vegetación y su exposición directa a los vientos y las mareas (Fig. 4).

Estos resultados demuestran la alta vulnerabilidad de la RBLP al ANM por el cambio climático. Es importante destacar que aunque la superficie de la RBLP haya sido decretada como área natural protegida, esto no garantiza necesariamente su efectividad de conservación. Como evidencia, encontramos que la tasa de cambio de cobertura vegetal en algunas áreas es alta, particularmente aquellas áreas con vegetación densa y que delimitan la reserva, es decir, que se encuentran fuera del área núcleo de conservación. Este cambio de cobertura vegetal debido a actividades humanas podría comprometer significativamente el potencial de migración de los petenes hacia el interior aumentando su vulnerabilidad y reduciendo a su vez su resiliencia.

El marco metodológico propuesto para evaluar la resiliencia de los petenes debido al cambio climático, ha demostrado ser una herramienta eficiente cuando los datos de alta precisión no se encuentran disponibles. Esta es una situación bastante común en muchos estudios, y en países como México, por lo tanto, este tipo de estudio podría permitir un mejor diseño de las estrategias de respuesta para hacer frente a perturbaciones de estos ecosistemas altamente vulnerables por lo que esperamos que nuestra investigación puede contribuir a este fin.

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ANEXOS

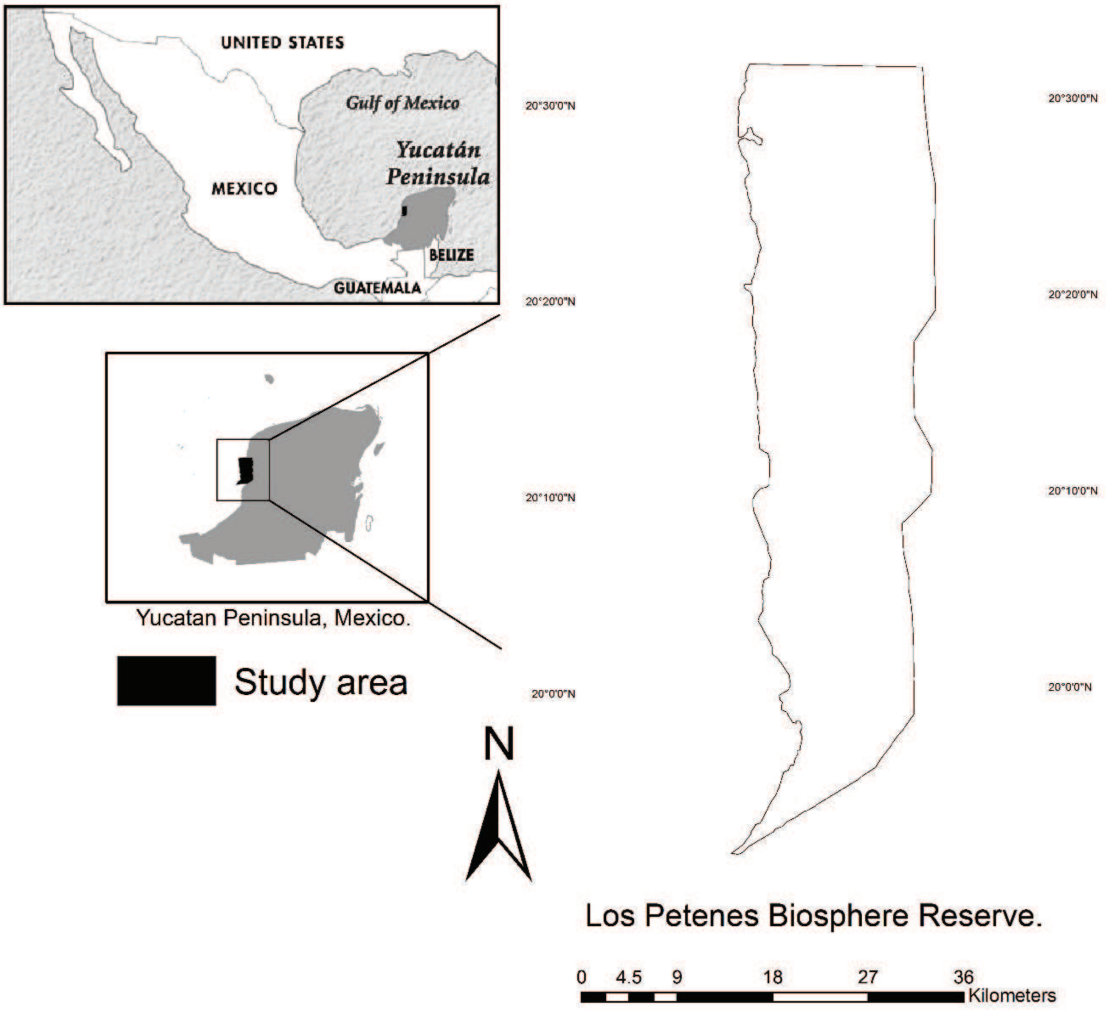

Fig. 1. Location of Los Petenes Biosphere Reserve in the Yucatan Peninsula, Mexico.

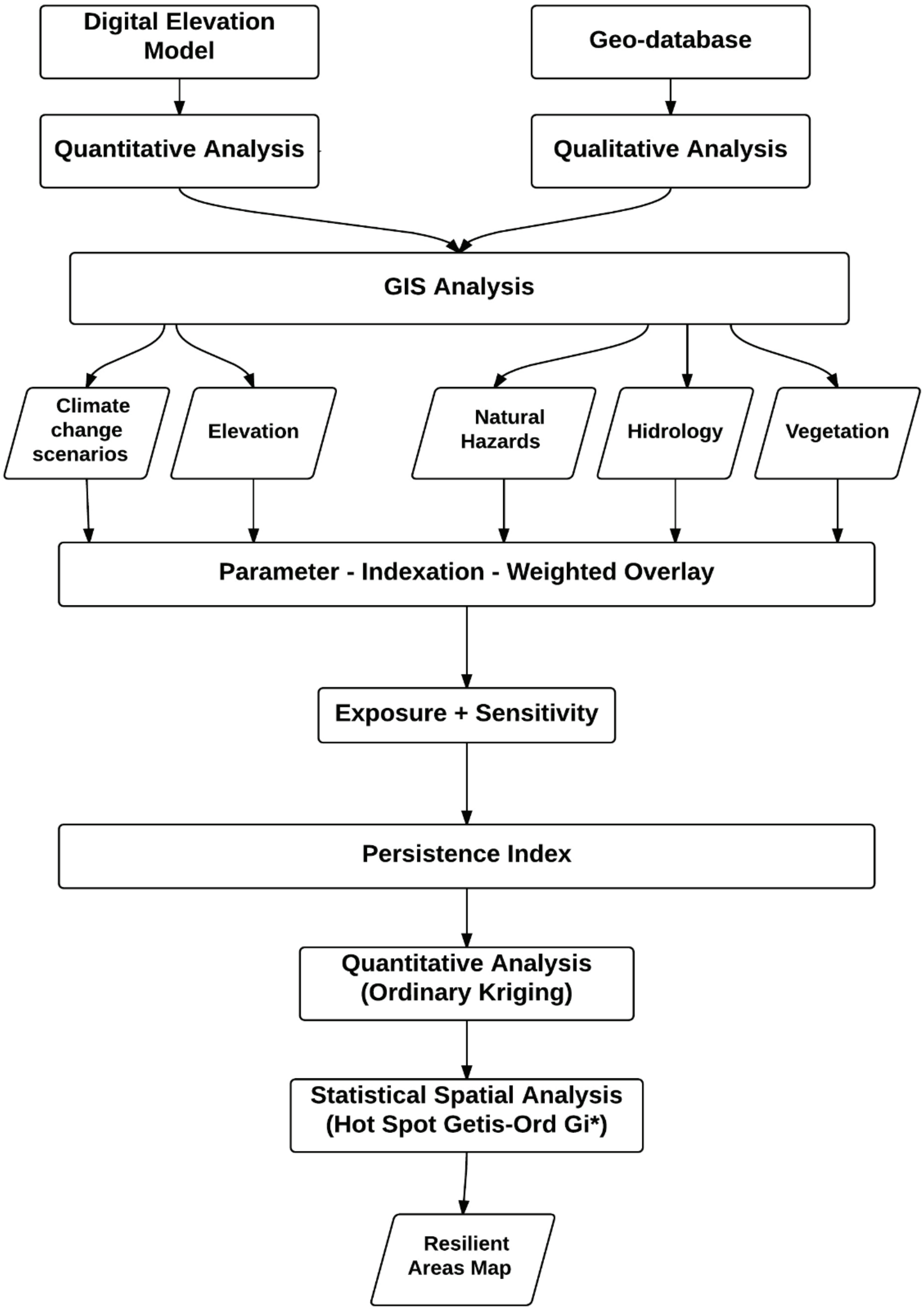

Fig. 2. Flow chart of the methodology used to assess hammock resilience to sea level rise due to climate change and to predict the most resilient areas at Los Petenes Biosphere Reserve.

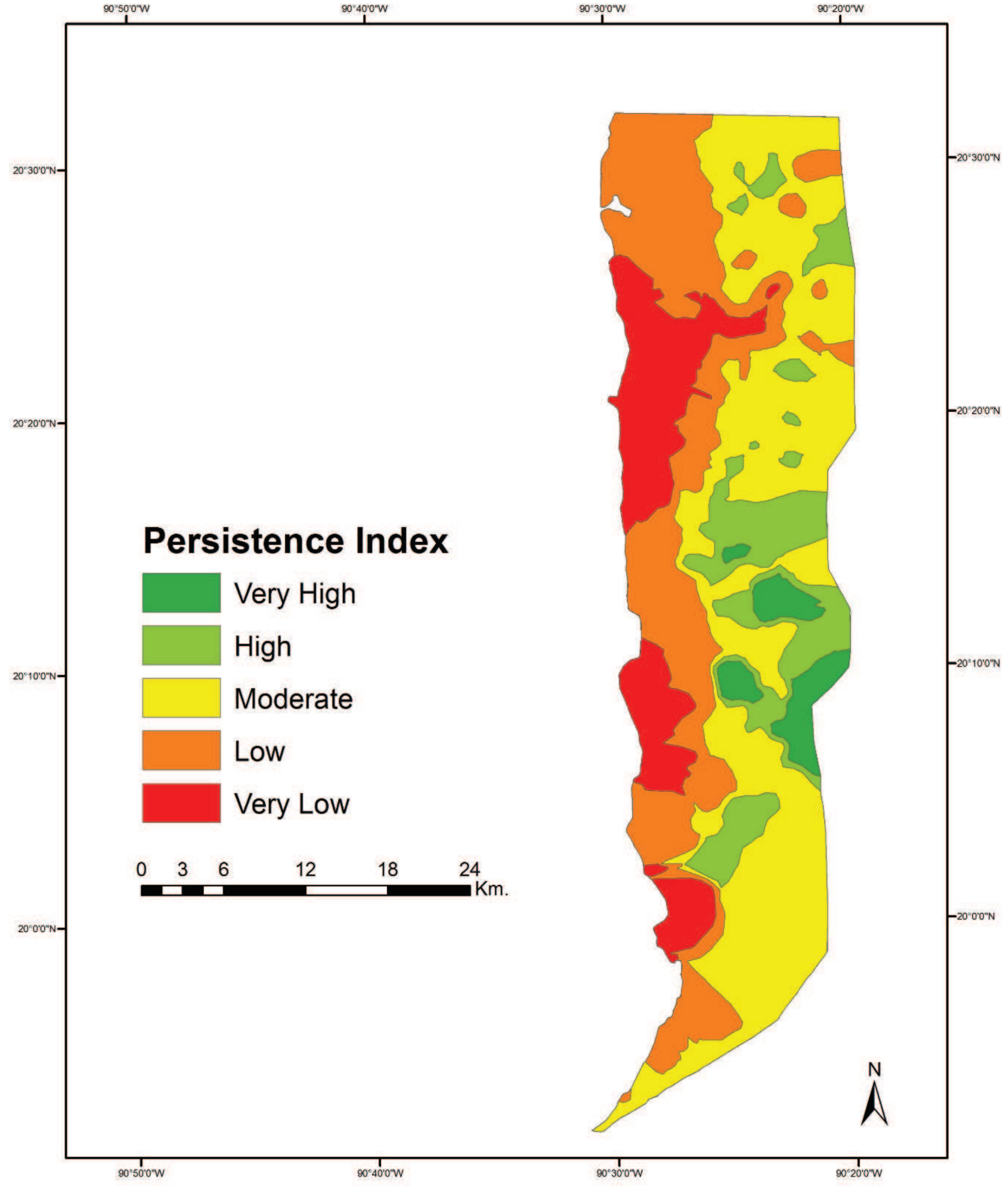

Fig. 3. Map of persistent areas at Los Petenes Biosphere Reserve.

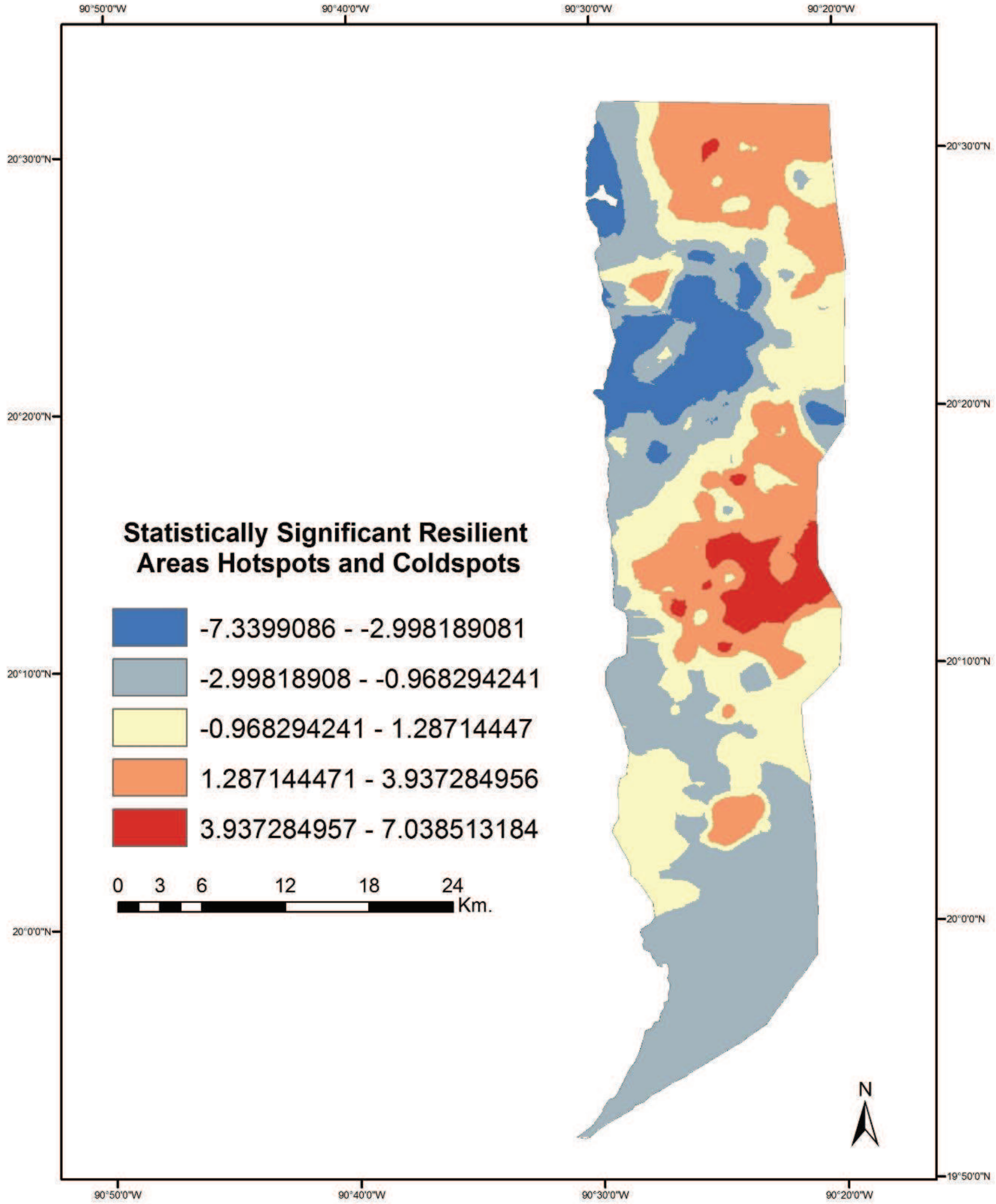

Fig. 4. Map of resilient areas at Los Petenes Biosphere Reserve. (Red and orange colors represent hotspots areas and blue and light blue, the coldspots areas of resilience).

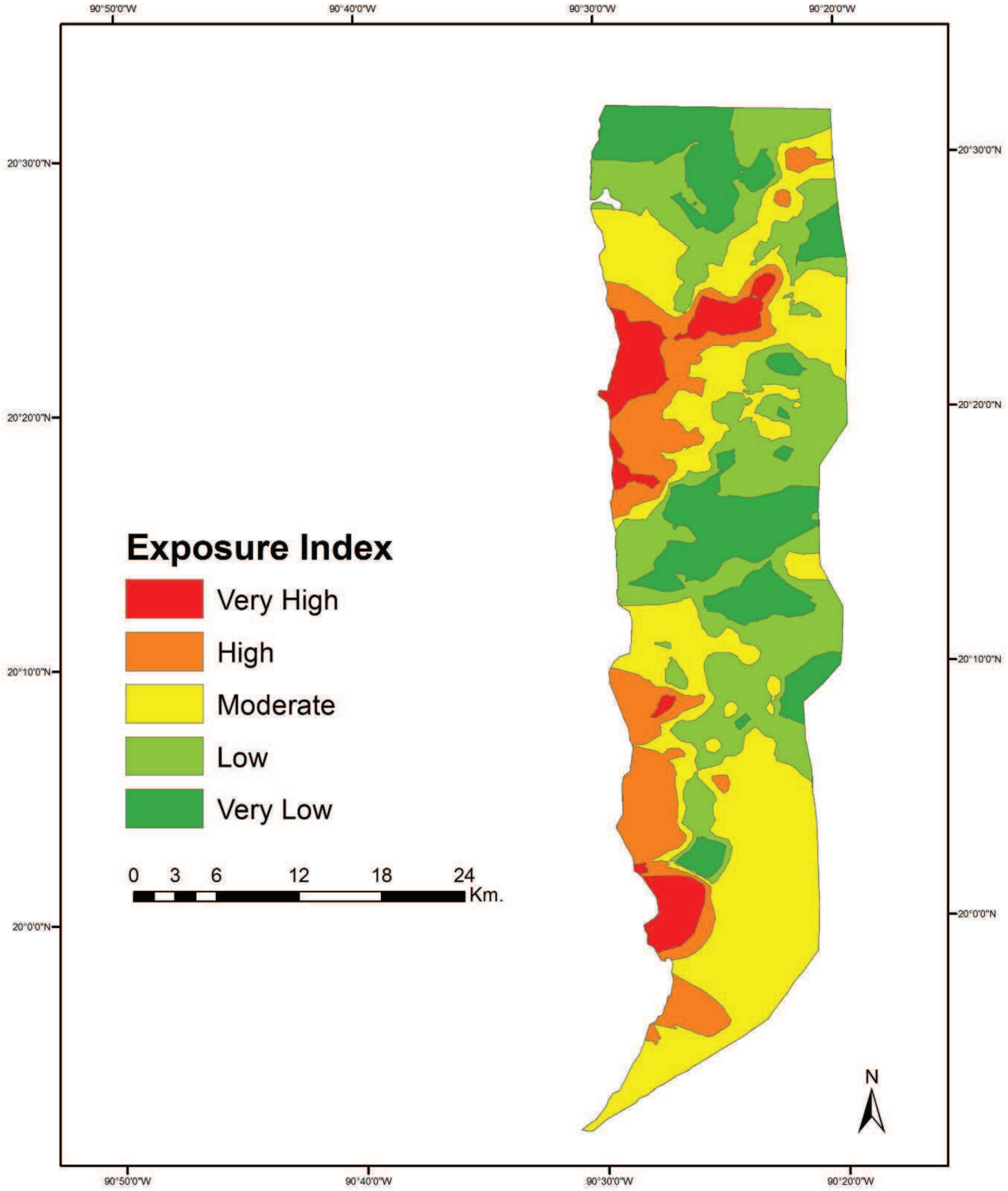

Fig. 5. Map of exposure to risk at Los Petenes Biosphere Reserve

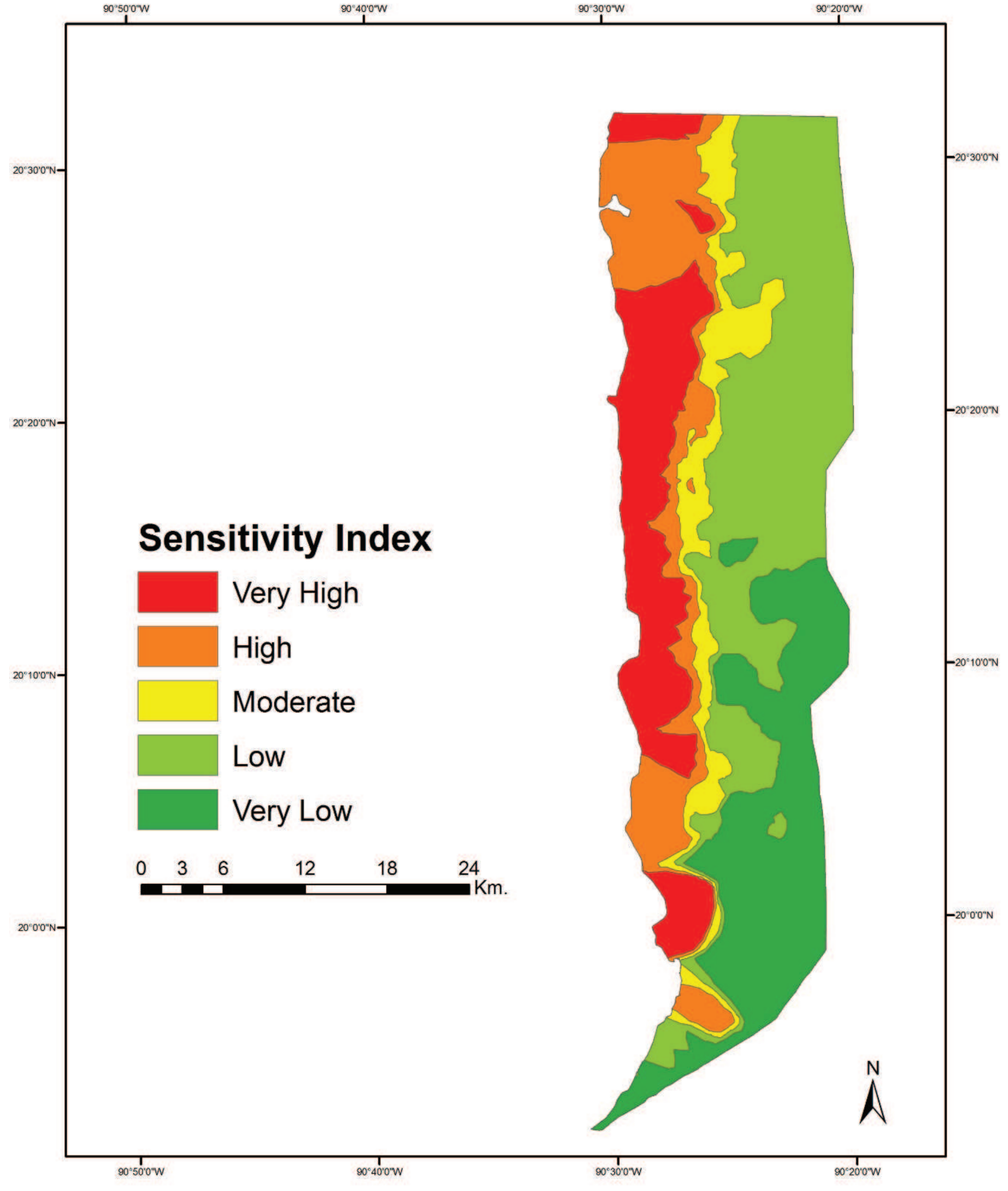

Fig. 6. Map of sensitivity areas at Los Petenes Biosphere Reserve.