UNIVERSITAT DE BARCELONA

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Lazzari, N., 2021. Assessment of the Spanish marine social-ecological associations and its implication for integrated management of coastal and marine systems. Doctoral thesis. Universidad de Barcelona. 160 pp.

Cover design and layout by Natali Lazzari.
Cover and back cover pictures: coastal marine landscape in Fuerteventura (Canary Islands, Spain) by Natali Lazzari.

UNIVERSITAT DE BARCELONA

Facultad de Biología
Departamento de Biología Evolutiva, Ecología y Ciencias Ambientales
Programa de doctorado en Biodiversidad (HDK04)
Conservación y Gestión de la Biodiversidad

Assessment of the Spanish marine social-ecological associations and its implication for integrated management of coastal and marine systems

Evaluación de las asociaciones socio-ecológicas marinas españolas y su implicación en la gestión integrada de los sistemas costeros y marinos

Memoria presentada por Natali Lazzari para optar al grado de doctora por la Universidad de Barcelona

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Centro de Estudios Avanzados de Blanes (CEAB-CSIC)
Barcelona, septiembre 2020

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A mis padres, hermana y
compañero de vida

Agradecimientos

Parece que es cierto, esta etapa que creía interminable llega a su fin y que mejor que cerrar la escritura de la tesis agradeciendo a todas las personas que han formado parte del camino y que lo han hecho muuuuucho más llevadero. Sin embargo, llegados a este punto me surge una cuestión, ¿cómo agradecer en unos pocos párrafos cinco años de aprendizaje, experiencias, vivencias… en definitiva, cinco años de vida? La verdad que no lo tengo muy claro, pero ¡allá voy!

Me gustaría comenzar agradeciendo a mi familia, pero no sólo por estos últimos años, sino por toda mi vida. A mis papis (y abuelo) quiero agradecerles la valentía que tuvieron al tomar la decisión de cruzar el charco y mudarse desde Buenos Aires a Fuerteventura, una preciosa isla de Canarias donde despertó mi pasión por el medio marino. Gracias por todos vuestros esfuerzos y sacrificios, por darme acceso a una educación de calidad, por apoyarme en cada una de mis decisiones (sabíamos que la biología no iba a darme fácilmente un trabajo estable ni un buen salario :)) y por no dejarme tirar la toalla en los momentos más difíciles de la vida. Sin vuestro apoyo y ánimos para seguir cada uno de mis sueños, no lo habría conseguido. Mami, agradezco cada una de nuestras "discusiones" sobre reciclaje, especies invasoras, pesca furtiva…, has hecho madurar mis argumentos y capacidad de discusión, pero también mi tolerancia hacia otras formas de pensar. Gracias por el amor hacia la naturaleza que me has inculcado desde pequeña, los nombres de plantas que no olvido y tu constancia para conseguir lo que uno desea. Papi, gracias por las tardes en la playa pescando seguidas de la exhaustiva identificación de las especies pescadas, han despertado no sólo mi interés por los peces, sino por la forma en la que el ser humano se relaciona con el medio marino. Agradezco que hayas aguantado mis charlas sobre las tallas mínimas permitidas, que hayas utilizado mis anzuelos sin muerte y, por supuesto, gracias por enseñarme la importancia de meditar la toma de decisiones importantes. Simplemente gracias papis por ser como son, soy muy afortunada de poder disfrutarlos y de tener un poquito de cada uno de vosotros.

También quiero agradecerte a ti princesa, por aguantar todas mis explicaciones sobre la vida marina que nos encontramos cada vez que vamos a la playa. Ya sabes (o deberías saber) que las "algas" alargadas que te tiraba en la playa para molestarte no son algas :P. Estoy segura de que cuando des clases a tus alumnos/as, utilizarás esas historietas para acercar la naturaleza a los más pequeños (¡más te vale!). También quería disculpar mis ausencias, muchas veces he dado demasiada prioridad a mi carrera absorbiendo tiempo que debería haberte dedicado como hermana mayor. ¡Estoy segura de que nos encargaremos de recuperarlo!

Por supuesto, gracias a mis cuatro angelitos, que desde donde estén, guían cada una de mis decisiones. Han sido el ejemplo de que, con trabajo y corazón, todo se consigue.

Qué decirte a ti, mi compañero de carrera, tesis, buceo… vida. Han sido cinco años de lucha mutua por sacar adelante un importante logro profesional para los dos, pero que no ha impedido que disfrutemos de cada momento y crezcamos a pasos agigantados como pareja. Gracias vida por aguantarme cada día, con mis altibajos, intentos de abandono de la tesis, picos de estrés y ansiedad… También quiero agradecer tu apoyo en todas las decisiones que he tomado, e incluso haberte unido a alguna de ellas (¿verdad yogui?). Aunque algunas hayan sido difíciles de tomar, siempre has estado a mi lado para darme un punto de vista totalmente distinto y esperanzador (¿recuerdas esa mañana en la UCA?). También por enseñarme que la mayoría de las veces la vergüenza no sirve de nada y que, si confío en mí misma, puedo con todo y más. Y gracias a tu familia por apoyarnos en nuestras locas aventuras. He disfrutado al máximo de todos esos viajes juntos y de cada uno de los sitios donde hemos vivido (aunque tenemos que reajustar la brújula para zonas más cálidas, ¿vale?). Infinitas gracias por hacerme feliz cada día, por haber disfrutado juntos de este camino y por ser el mejor compañero de vida. Estoy ansiosa por saber qué nos depara el futuro.

Berta, ¡¡ya se acabaaa!! Y la verdad no sé quién tenía más ganas de cerrar este capítulo :). *Sólo decirte, que no podría imaginar una mejor directora de tesis y que soy muy afortunada por tenerte también como amiga. Gracias por cada minuto de tu tiempo (los que te conocemos sabemos lo valiosos que son), por apoyarme en cada congreso/estancia/curso al que decidía ir y por ayudarme a creer en mí misma. Gracias por preocuparte constantemente por mi estado mental y brindarme herramientas que me ayuden a balancear mi ratio personal/profesional, han sido clave en el desarrollo de esta tesis y serán mi dogma de futuro. Gracias también por acogerme en Lüneburg y hacerme sentir como en casa. Me has abierto los ojos al mundo en muchos aspectos y acercado a experiencias que no estaban del todo en mis planes (nos queda una sauna pendiente de la última estancia y un baño en el lago). Y por supuesto, gracias por enseñarme que hay vida más allá de la tesis y del mar. Ahora voy por todos lados buscando pájaros, aunque ni de lejos consiga saber cuáles son.*

Mikel, nuestras cenas en el CEAB terminando de cerrar proyectos me han enseñado que los deadlines *están para ponernos a prueba :P. Quién necesita saltar en parapente, cuando diez minutos antes de que cierre el plazo de un proyecto tiene que modificar todo el presupuesto ¡Adrenalina pura :)! Más allá de estas experiencias, me has enseñado la importancia de transmitir la ciencia de la forma más atractiva e innovadora posible. Gracias a ello, he descubierto una faceta artística que desconocía y seguro aplicaré a mi futura investigación. Agradecerte que, como director de tesis, me has enseñado desde un principio la importancia que tiene para una investigadora ser totalmente independiente, y aunque el camino no ha sido fácil, es una lección que* *me servirá para el resto de mi carrera. Gracias a los dos finalizo esta etapa satisfecha con mi evolución, segura de mi misma e impaciente por el futuro que me espera.*

Creu y Dolors, gracias por estar siempre dispuestas a ayudar en todo lo necesario y solventar todas las dudas que han surgido a lo largo de estos años (que no han sido pocas :D).

Gracias a tod@s l@s amig@s de siempre, que han estado ahí animando y apoyando, incluso a la distancia (especialmente a María José, Borja, Lidia, Ale, Pepe).

Las idas y venidas de la tesis me han brindado la oportunidad de conocer muchas personas lindas a las que me gustaría dedicarles las siguientes líneas:

Laura y María, llegaron como estudiantes de Máster al laboratorio en el CEAB, y sufrimos juntas experimentos, largas semanas de muestreo, horas interminables de ordenador, estrés pre-congresos y un mes de convivencia un poco gypsy :P. *También nos tocaron momentos personales más difíciles, que nos hicieron devolver los pies a la tierra y tomar perspectiva de la que era nuestra realidad. ¡Gracias por amenizar con vuestra presencia parte de esta locura de tesis! Por cierto, Laura nunca te olvides que a las 11:00 se mete viento, así que hay que ir a bucear tempranito :)*

En Blanes conocí también a Ana y Rafa, dos personas que nunca han dudado en ayudarme en lo que hiciera falta, además de ofrecerme su casa en innumerables ocasiones. Gracias por estar siempre ahí y brindarme ese toque de humor tan característico vuestro, no saben cuántas mañanas y tardes en el centro me habéis alegrado :). *Agradecer también a tod@s los que me ayudaron de una u otra forma en el CEAB (Ferrán, Ramón, Gemma, Carmela, Margarita, Marta, Ángel, Roger, Maribel).*

Una importante parte de la tesis tuvo lugar en la Universidad de Cádiz, donde aprendí a la fuerza a compaginar tesis con trabajo. Fue un año y medio muy duro y agotador, pero me sirvió para aprender a disfrutar de las pequeñas cosas, como los desayunos en la cafetería de la uni con Silvia, o la cervecita de los viernes con Tote. Gracias doctores por vuestros consejos y paciencia en el laboratorio :) También gracias a Laureana y Chiqui por acogerme en sus laboratorios y por mirar un poco hacia un lado cuando había poco trabajo y yo aprovechaba para ponerme con la tesis, esos ratitos me daban la vida. Disfruté mucho de esa etapa con todos vosotros: José Ramón, Cuca, Alberto, Tito, Ismael, Aglaya, con el grupo de garantía juvenil y con el equipo de química física. Me enseñaron la parte más humana del mundo científico. In Cadiz, I also met one of the happiest and lovely girls, Kirsten. I never thought that we could maintain our friendship with such distance, but look!! I almost talk more with you than with my family :). Thanks for encouraging me with the thesis, and for trying to improve my English (you still have a lot of work :P)!

Alemania fue otro de los destinos clave de esta tesis. Fue un placer compartir paseos en bici por Lüneburg, currywurst, mercadillos navideños, glühwein, hogueras, salidas de fin de semana y alguna que otra conversación sobre la tesis y los sistemas *socio-ecológicos con Nati, Maraja, Paty, Rodri, David, Kata, Steffen, y por supuesto, Berta. Gracias por hacerme disfrutar de la tesis de una manera muy diferente a la que estaba acostumbrada. Agradezco también que me hayáis incluido en vuestras reuniones de cuarentena, ¡fueron realmente divertidas!*

En Chile pasé varios meses muy intensos en términos de trabajo, pero no por ello me olvidé de disfrutarlos. A todas aquellas personas con las que compartí asados, piscos, piñones de araucaria, sopaipillas y kuchen de nuez (Claudia, Antonio, Don Iván, Simone, Marina, Alex, Sergio, Evie y ECIM en general) ¡gracias! María José, agradezco que me brindaras tu casa sin dudarlo y nuestras conversaciones sobre conciliación familiar. Sigo creyendo que compaginar investigación y familia es muy difícil, pero tú me has demostrado que es totalmente posible. Y a ti Stefan, gracias por tu valioso tiempo :). Durante esta etapa, que tuve la fortuna de compartir con Jose, conocimos a Clara y Monique, dos doctorandas con las que compartimos numerosas noches de conversaciones sobre la tesis, siempre con la fiel compañía de una botella de vino y alguna que otra pizza. Me siento muy afortunada de haberlas conocido, y de continuar nuestra amistad más allá de la estancia. ¡Tendremos que organizar una reunión de doctor@s próximamente, por supuesto, con patacones y brigadeiros!

El buceo representó una importante parte de esta tesis, por ello me gustaría agradecer a todos aquellos centros y clubes de buceo que facilitaron los muestreos de esta tesis, y con los que espero seguir colaborando. Gracias a tod@s l@s buceador@s RLS que contribuyeron en alguna fase de la recogida de datos. And, thanks to the Reef Life Survey team (especially Rick, Graham, and Toni) for inspiring me to continue with this terrific project. You demonstrate that a different way of citizen science is possible.

Finalmente, agradecer al Club de buceo Ánfora en Melilla y al equipo INBIOMAR I e INBIOMAR II (en especial a Ángel, Domingo, Alberto, Laura, Juanjo y Manu), esperemos poder continuar con la tercera entrega de este gran proyecto entre amigos, siempre y cuando el levante nos lo permita :P. *A los componentes del Club de buceo Oxigeno en Fuerteventura (especialmente a Araceli, Emilio y Dani), por confiar en nuestras ideas de proyecto, por convertir en complicadas las entradas imposibles al agua, y, especialmente, por sacar el barco al agua cada vez que voy a bucear (ironía) :D Y a Javi, del Centro de buceo Burbujas en Ceuta, por recibirnos con los brazos abiertos cada vez que decidimos sumergirnos en sus fondos.*

Podría extenderme más agradeciendo todas las experiencias que hemos vivido junt@s a lo largo de estos años, pero creo que es momento de ir terminando. Simplemente GRACIAS a tod@s por ser parte de esta tesis y hacer que la recuerde con una sonrisa de oreja a oreja.

¡Espero seguir contando con vosotr@s en las aventuras que me depare el futuro!

Funding

This thesis has been partially funded by the projects MARINERES, CGL2013-49122-C3-1-R of the Spanish Ministry of Economy and Competitiveness; DIVERSAT, RTI2018-098970-B-100 of the Spanish Ministry of Science, Innovation and Universities; INBIOMAR, PRCV00676 that count with the support of the Biodiversity Foundation of the Ministry for the Ecological Transition and the Demographic Challenge; and the Ibero-american Grants. Santander researcher fellowship, of the Santander Bank.

Summary

The alarming rate of marine biodiversity loss calls for new strategies of understanding and accounting for human-nature relationships. Anthropogenic impacts are the main drivers of changes in coastal and marine systems (hereafter coastal systems), where more than 50% of the world's human population lives. Such cumulative anthropogenic impacts are leading to a dangerous decline in the ecosystem functions and resilience of coastal systems. However, the lack of knowledge about how the social and ecological dimensions interrelate in the coastal systems may lead to failure in protecting, not only nature but also the society that relies on it.

This thesis aims to contribute to the social-ecological knowledge of coastal systems by assessing the social-ecological associations of the Spanish coastal and marine communities. In doing so, it develops a methodological approach for defining and spatially identifying coastal and marine social-ecological systems, assesses the relationship between marine biodiversity and the socio-economic and marine environmental characteristics of the social-ecological systems, and detects the *hotspots* of social-ecological vulnerability in the Spanish temperate coastal system.

The findings presented in this thesis show that applying innovative methods, it is possible to untangle the complexity of social-ecological interactions. This thesis identifies the associations between the socio-economic and marine environmental aspects that form the coastal marine social-ecological systems of the Mediterranean coast of Andalusia, and how these social-ecological aspects relate to biodiversity metrics. Deeping in these associations, the results of this thesis identify the most social-ecological vulnerable areas in the Spanish coastline, which require immediate sustainable management actions.

Within the context of global changes and biodiversity loss, this thesis challenges conventional studies with an innovative perspective that advance the understanding of social-ecological associations, and provide the needed knowledge to identify sustainable management strategies for building more resilient temperate coastal systems.

Resumen

El alarmante ritmo de pérdida de la biodiversidad marina exige nuevas estrategias para comprender las relaciones entre el hombre y la naturaleza. Los impactos antropogénicos son los principales impulsores de cambio en los sistemas costeros y marinos (en adelante, sistemas costeros), donde vive más del 50% de la población humana del mundo. La acumulación de estos impactos antropogénicos está provocando una peligrosa disminución de las funciones de los ecosistemas y de la capacidad de recuperación de los sistemas costeros. Sin embargo, la falta de conocimientos sobre la forma en que las dimensiones sociales y ecológicas se interrelacionan en los sistemas costeros, puede conducir a un fracaso en la protección no sólo de la naturaleza sino también de la sociedad que depende de ella.

Esta tesis doctoral tiene por objeto contribuir al conocimiento socio-ecológico de los sistemas costeros mediante la evaluación de las asociaciones socio-ecológicas de las comunidades costeras y marinas españolas. Para ello, desarrolla un enfoque metodológico para definir e identificar espacialmente los sistemas socio-ecológicos costeros y marinos, evalúa la relación entre la biodiversidad marina y las características socioeconómicas y ambientales marinas de los sistemas socio-ecológicos y detecta focos de vulnerabilidad socio-ecológica en el sistema costero templado español.

Los resultados presentados en esta tesis doctoral muestran que aplicando métodos innovadores es posible desenredar la complejidad de las interacciones socio-ecológicas. En esta tesis doctoral se identifican las asociaciones entre los aspectos socioeconómicos y ambientales marinos que conforman los sistemas socio-ecológicos marinos costeros de la costa mediterránea de Andalucía, y cómo estos aspectos socio-ecológicos se relacionan con la biodiversidad. Profundizando en estas asociaciones, los resultados de esta tesis doctoral identifican las zonas más vulnerables socio-ecológicamente del litoral español, las cuales requieren de una gestión sostenible inmediata.

En el contexto de cambio mundial y pérdida de biodiversidad, esta tesis desafía los estudios convencionales con una perspectiva innovadora que avanza en la comprensión de las asociaciones socio-ecológica, y proporciona el conocimiento necesario para identificar estrategias de gestión sostenible para construir sistemas costeros templados más resistentes.

Contents

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List of abbreviations and acronyms

ACSS	Adaptive Capacity of the Social System
CMSES	Coastal Marine Social-Ecological System
db-RDA	distance-based Redundancy Analysis
DF	Dependency on Fishing
DT	Dependency on Tourism
EES	Exposure of the Social System to Ecological Vulnerability
FP	Fishing Pressure
HCA	Hierarchical Cluster Analyses
ICZM	Integrated Coastal Zone Management
KMO	Kaiser-Meyer-Olkin
LRP	Pressure from Local Recreational Activities
MAPA	Ministry of Agriculture, Fisheries and Food
MEC	Marine Environmental Class
NLRP	Pressure from Non-Local Recreational Activities
nMDS	non-Metric Multidimensional Scaling
PC	Principal Component
PCA	Principal Component Analysis
RaoQ	Rao's Quadratic entropy
RDA	Redundancy Analysis
RFC	Recovery Potential of the Fish Community
RLS	Reef Life Survey
SEC	Socioeconomic Class
SEPE	Public Service State Employment
SES	Social-Ecological System
SEV	Social-Ecological Vulnerability
SIMA	Andalusian Multi-Territorial Information System
Spanish MEA	Spanish Millennium Ecosystem Assessment
SST	Sea Surface Temperature

List of articles

Indicating journal impact factor (IF), and quartile (Q):

Paper I. Spatial characterization of coastal marine social-ecological systems: insights for integrated management. **Natali Lazzari**[1], Mikel Becerro[1], Jose A. Sanabria-Fernandez[1], Berta Martín-López[2] (2019) Environmental Science & Policy 92: 56-65. IF: 4.816; Q1

Paper II. Alpha and beta diversity across coastal marine social-ecological systems: Implications for conservation. **Natali Lazzari**[1], Berta Martín-López[2], Jose A. Sanabria-Fernandez[1], Mikel Becerro[1] (2020) Ecological Indicators 109: 105786. IF: 4.490; Q1

Paper III. Assessing social-ecological vulnerability of coastal systems to fishing and tourism. **Natali Lazzari**[1], Mikel Becerro[1], Jose A. Sanabria-Fernandez[1], Berta Martín-López[2]. Submitted to Science of the Total Environment. IF: 6.551; Q1

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Author contributions

NL: Natali Lazzari; MB: Mikel Becerro; BML: Berta Martín-López; JASF: Jose A. Sanabria-Fernandez

Paper I.	NL, MB, and BML developed the idea for the article together. BML led the theoretical framing, analysis, and writing. NL collected the data, developed the analysis, and contributed to the writing. MB contributed to the writing and, together with JASF, they contributed to the discussion of theoretical implication.
Paper II.	NL had the original idea for the article, collected data, undertook the analysis, and wrote the paper. BML contributed to the writing and discussion of theoretical framing. JASF contributed to data collection and analysis. MB led the analysis and writing.
Paper III.	NL developed the original idea and led the data collection, analysis, and writing. JASF contributed to data collection and discussion of the conceptual implications. MB contributed to the writing. BML contributed to the writing and discussion of the theoretical framing.

Additional publications

- Building up marine biodiversity loss: artificial substrates decrease the number and abundance of low occupancy benthic and sessile species. Jose A. Sanabria-Fernandez, **Natali Lazzari**, Rodrigo Riera, Mikel Becerro (2018) *Marine Environmental Research* 140: 190-199. oi.org/10.1016/j.marenvres.2018.06.010

- Marine protected areas are more effective but less reliable protecting fish biomass than fish diversity. Jose A. Sanabria-Fernandez, **Natali Lazzari**, Rodrigo Riera, Mikel Becerro (2019) *Marine Pollution Bulletin* 142: 24-32. doi.org/10.1016/j.marpolbul.2019.04.015

- Quantifying patterns of resilience: what matters is the intensity, not the relevance, of contributing factors. Jose A. Sanabria-Fernandez, **Natali Lazzari**, Mikel Becerro (2019) *Ecological Indicators* 107: 105565. doi.org/10.1016/j.ecolind.2019.105565

- Reef Life Survey: Establishing the ecological basis for conservation of shallow marine life. Graham J. Edgar, Antonia Cooper, Susan C. Baker, William Barker, Neville S. Barrett, Mikel A. Becerro, Amanda E. Bates, Danny Brock, Daniela Ceccarelli, Ella Clausius, Marlene Davey, Tom R. Davis, Paul Day, Andrew Green, Sam R. Griffiths, Jamie Hicks, Iván A. Hinojosa, Ben Jones, Meryl F. Larkin, **Natali Lazzari**, Scott D. Ling, Peter Mooney, Elizabeth Oh, Alejandro Pérez-Matus, Jacqueline B. Pocklington, Rodrigo Riera, Jose A. Sanabria-Fernandez, Yanir Seroussi, Ian Shaw, Derek Shields, Joe Shields, Margo Smith, German A. Soler, Jemina Stuart-Smith, John Turnbull, Rick D. Stuart-Smith (under review) *Biological Conservation*

Directors' report

Dr. Mikel Becerro and Berta Martín-López, as supervisors of the thesis entitled 'Assessment of the Spanish marine social-ecological associations and its implication for integrated management of coastal and marine systems',

INFORM that the research developed by Natali Lazzari for her Doctoral Thesis has been organized in 7 sections, which include a General Introduction, Objectives, General Discussion, and Conclusions, in addition to three chapters summarizing the empirical investigations. Each one of these three chapters correspond to a scientific paper published or in process of publication in international peer-reviewed journals, as it is listed below (Indicating journal impact factor (IF 2019), and quartile (Q)).

Chapter I: Spatial characterization of coastal marine social-ecological systems: insights for integrated management. **Natali Lazzari**, Mikel Becerro, Jose A. Sanabria-Fernandez, Berta Martín-López (2019) *Environmental Science & Policy* 92: 56-65. IF: 4.816; Q1

Chapter II: Alpha and beta diversity across coastal marine social-ecological systems: Implications for conservation. **Natali Lazzari**, Berta Martín-López, Jose A. Sanabria-Fernandez, Mikel Becerro (2020) *Ecological Indicators* 109: 105786. IF: 4.490; Q1

Chapter III: Assessing social-ecological vulnerability of coastal systems to fishing and tourism. **Natali Lazzari**, Mikel Becerro, Jose A. Sanabria-Fernandez, Berta Martín-López. Submitted to Science of the Total Environment. IF: 6.551; Q1

We also CERTIFY that, Natali Lazzari has leaded the research presented in this thesis. She has discussed the original ideas with the supervisors, leaded the field work, data collection, data analyses, and manuscript writing. Below, the specific contribution of Natali Lazzari in each chapter. NL: Natali Lazzari, MB: Mikel Becerro, BML: Berta Martín-López and JASF: Jose A. Sanabria-Fernandez.

Chapter I: NL, MB and BML developed the idea for the article together. BML led the theoretical framing, analysis, and writing. NL collected the data, developed the analysis and contributed to the writing. MB contributed to the writing and, together with JASF, they contributed to the discussion of theoretical implication.

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Chapter III: NL developed the original idea, and led the data collection, analysis and writing. JASF contribute to data collection and discussion of the conceptual implications. MB contributed to the writing. BML contributed to the writing and discussion of the theoretical framing.

Finally, we certify that the research work presented has never been used as contribution to or part of any other national or international Doctoral Thesis.

Thesis supervisor,
Mikel Becerro
Centro de Estudios
Avanzados de Blanes
(CEAB-CSIC)

Thesis supervisor,
Berta Martín-López
Leuphana University
of Lüneburg

General introduction

Picture: School of Mediterranean damselfish (*Chromis chromis*) in Chafarinas Islands (Spanish territories in the northern coast of Africa) by Natali Lazzari

1

General introduction

1.1. Background

1.1.1. Status of marine biodiversity

Many pressures threaten marine biodiversity, from natural hazards (e.g., hurricanes, volcanos, or storms) to anthropogenic impacts (e.g., habitat fragmentation, overfishing, or pollution). The effects of human activities have led to significant changes in the global environment driving our planet into a new geological period named Anthropocene (Crutzen, 2002; Steffen et al., 2007; Fig. 1.1). Marine systems are not spared, and the Anthropocene in this system is experiencing an alarming loss of global biodiversity

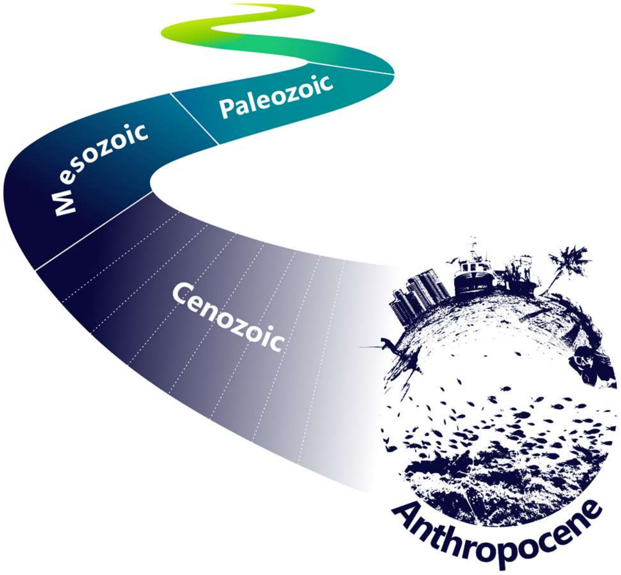


Figure 1.1. Geological time scale representing the Paleozoic, Mesozoic, and Cenozoic Eras ending in the Anthropocene Epoch.

(Luypaert et al., 2020). Almost forty percent of the marine biodiversity have been lost globally in the last 40 years, and more than 50% of the marine species of the world may stand on the brink of extinction by 2100 if the current rate of change continues (UNESCO, 2018; WWF, 2016; Fig. 1.2).

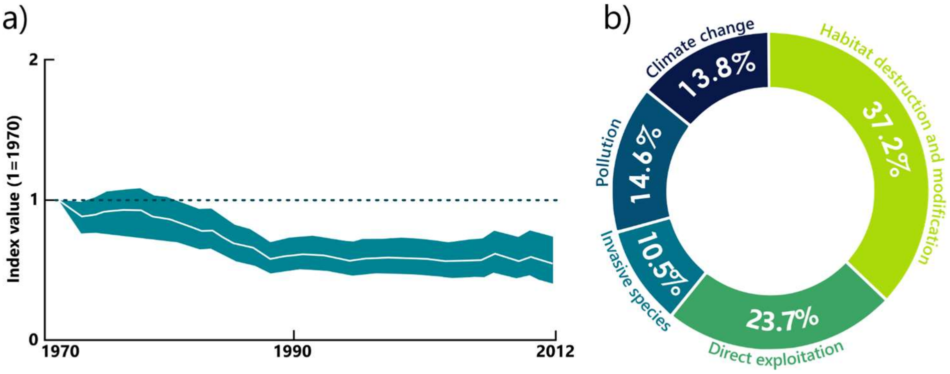


Figure 1.2. Representation of (a) the marine living planet index between 1970 and 2012, showing the declining trend in marine populations, and (b) the relative importance of anthropogenic stressors to species threatened with extinction. Adapted from WWF, 2016 and Luypaert et al., 2020.

Traditionally, the number of species, i.e., species richness, has been a critical indicator of ecosystems' status and the focus of conservation programs (Gaston, 2000; Bellwood and Huges, 2001; Hillebrand, 2004). Yet, beyond species richness, recent studies evidence that the ecological functions performed by these species are highly relevant, too (Stuart-Smith et al., 2013; Mouillot et al., 2014; Olivier et al., 2018). The shift from species to functions has revealed an overlooked value of temperate regions, which represent global *hotspots* of functional diversity (Stuart-Smith et al., 2013; Fig. 1.3). Temperate regions show higher functional diversity than their tropical counterparts, i.e., temperate species have a more significant contribution to ecosystem functioning than tropical species (Stuart-Smith et al., 2013). Comprehensive knowledge about the interaction of both species and functional diversity with non-biological factors is a must for the effective management of marine ecosystems. Marine biodiversity has become a conservation priority under numerous international agreements such as the Sustainable Development Goals (i.e., SDG 14) or the Convention on Biological Diversity, who has suggested to halt the diversity net loss by 2030 as a goal for the post-2020 Global Biodiversity Framework. In addition, to prioritize the conservation of the oceans, UNESCO has announced that 2021–2030 will be the Decade of Ocean Science for Sustainable Development (UNESCO, 2018; Visbeck, 2018). All these initiatives emphasize the need for interdisciplinary studies to reduce the human-derived loss of biodiversity and to preserve the ecological state and functions of the marine ecosystems.

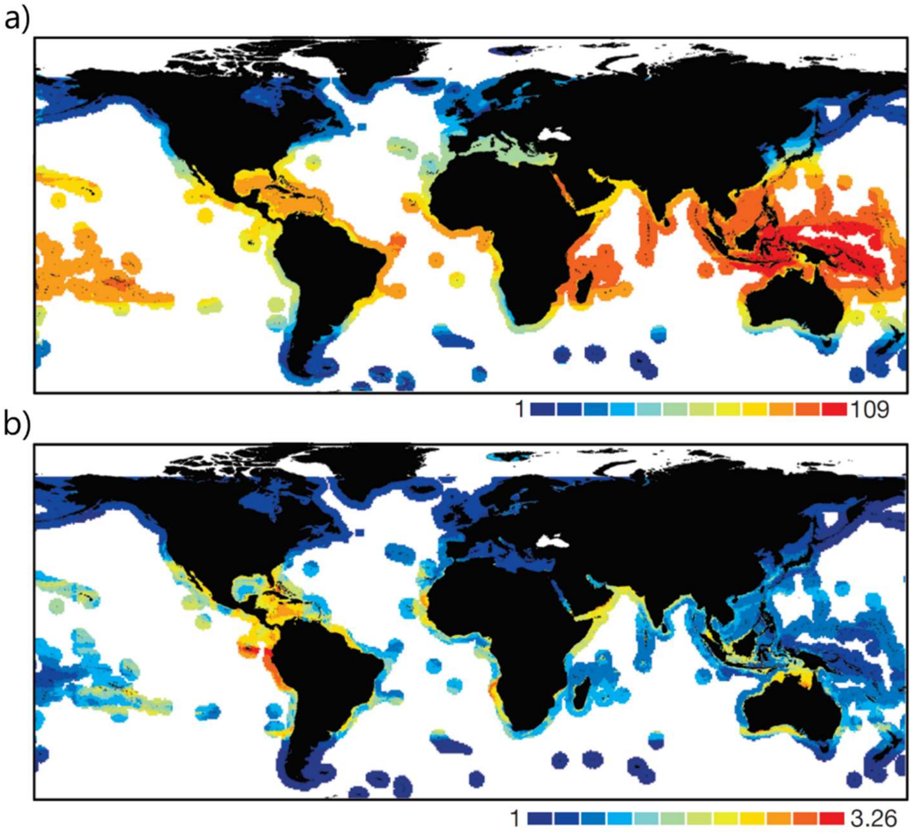


Figure 1.3. Global fish diversity patterns. (a) Species density decreasing with higher latitudes and (b) abundance-weighted functional diversity showing scattered *hotspots* in temperate regions. Adapted from Stuart-Smith et al., 2013.

Biodiversity loss has led to the disruption of ecosystem functions and resilience, increasing the vulnerability of many ecosystems (Cinner et al., 2013). Resilience and vulnerability are related concepts that stem from the natural and the social sciences, respectively (Adger 2006; Gallopi 2006).

Often referred to as opposite sides of the same coin, the reality is more complicated as both concepts have multiple definitions that challenge an accurate understanding of their genuine relationship (Folke et al., 2002; Gallopi 2006; Miller et al., 2010). Most researchers understand resilience as the intrinsic capacity of a system to absorb disturbance before changing to another state (Holling, 1973; Gunderson, 2000; Miller et al., 2010). Vulnerability, however, emphasizes the magnitude at which systems are unable to cope with disturbances (Adger 2006). Recently, a new generation of social-ecological studies on coastal systems has focused on disentangling the relationship between the social and ecological vulnerability components, providing information about priority areas for action (Marshall et al., 2009; Thiault et al., 2017). Understanding the social-ecological vulnerability of coastal systems is essential to developing management actions that are oriented to build resilience and avoid the collapse of coastal and marine SES (Marshall et al., 2009; Thiault et al., 2017). This thesis not only fosters the inclusion of biodiversity aspects as an indispensable part of coastal and marine SES assessment but also provides the methodological tools for its integration.

1.1.2.Coastal and marine systems

Coastal and marine systems (hereafter coastal systems) are geographic areas with consistent social-ecological interactions within them that differ from those of their adjacent areas (Leenhardt et al., 2015). Coastal systems are, therefore, affected by both social and ecological threats (Neumann et al., 2017). Coastal systems support the livelihood of a large proportion of the world's human population and provide a large amount of the human protein intake (Agardy et al., 2005; FAO, 2012). Currently, 50% of the total population and 60% of the world’s largest cities are on the coastline, and predictions indicate that both proportions will continue to grow (Neumann et al., 2015; UNFPA, 2009; IPCC, 2007; Fig. 1.4). People's migration to coastal areas is strongly related to the positive contribution of the coastal biodiversity to the people’s quality of life through the supply of several Nature’s Contributions to People, including food provision, climate regulation, and aesthetic satisfaction, to name a few (Burak et al., 2004;

Neumann et al., 2015). Nevertheless, cumulative anthropogenic impacts such as habitat fragmentation, overexploitation of marine resources, or climate change are jeopardizing the future sustainability of coastal systems and, ultimately, people's quality of life (Halpern et al., 2015; Díaz et al., 2019).

There is strong evidence that human-derived activities are the main drivers of change in marine systems (Crain et al., 2008; Halpern et al., 2008).

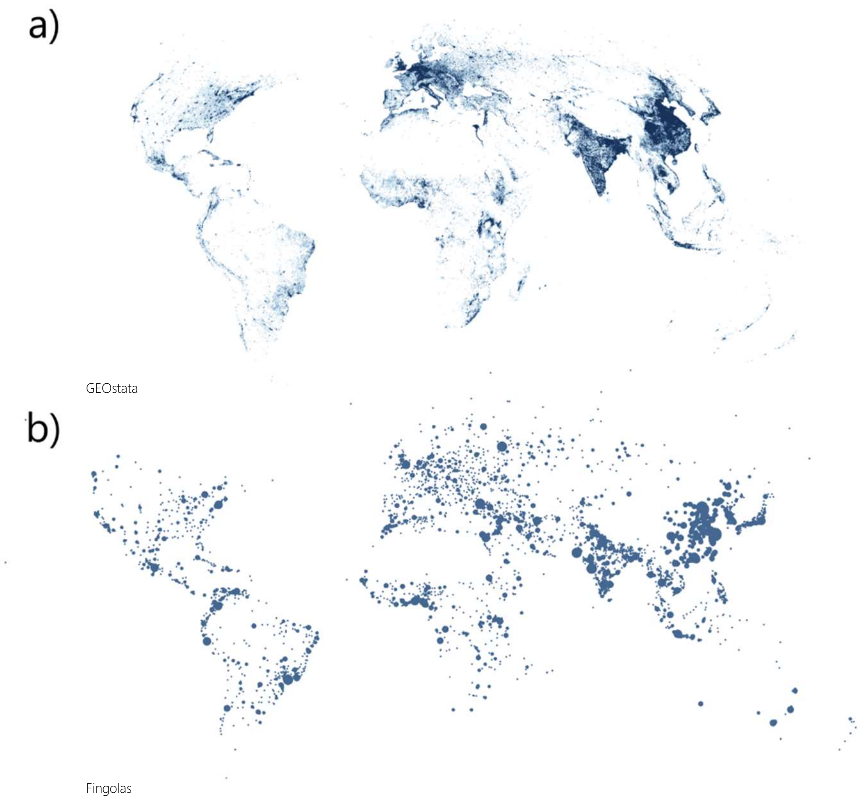


Figure 1.4. Human concentration in coastal areas. (a) World population density in 2015 and (b) spatial distribution of cities over 100.000 inhabitants.

Planners and policy-makers, however, often design management measures without considering the actual interactions between the social and the ecological dimensions of coastal systems (Leenhardt et al., 2015). A useful tool to reduce the impacts of anthropogenic activities is the establishment of marine protected areas (Micheli et al., 2012; Guidetti et al., 2014). Yet, the establishment of marine protected areas without understanding the social-ecological relationships may lead to failure in protecting the nature's contributions to people, such as the aesthetic satisfaction or, even, essential components of marine systems such as biodiversity (Sanabria-Fernandez et al., 2019). This thesis contributes to building up knowledge of the social-ecological associations present in coastal systems, which remains essential to develop efficient management practices, including in marine protected areas.

1.2.Conceptual framework: social-ecological systems (SES)

SES refer to the interaction of social and bio-geophysical dimensions on multiple temporal and spatial scales (Berkes and Folke 1998; Liu et al., 2007; Fig. 1.5). There is an increasing trend in the number of SES studies over the last decades, with almost 13,000 publications on SES published since 1970 (Colding and Barthel, 2019). This trend responds to the need for comprehensive studies focused on understanding the associations between social and ecological dimensions, and its relevance in achieving sustainability (Glaser et al., 2012; Binder et al., 2013; Rissman and Gillon, 2017; Colding and Barthel, 2019). Numerous theoretical frameworks have risen in the last decades to overcome this need, yet no approach is a panacea, and there is no single way to unveil social-ecological associations (Colding and Barthel, 2019). Beyond the multiple possible approaches, two main difficulties pursue the development of SES studies. First, SES studies are commonly biased by a strong focus on socio-economic aspects, leaving aside critical ecological issues such as biodiversity (Rissman & Gillon, 2017). A recent review conducted by Rissman & Gillon (2017) evidenced that only 12% of the studies included biodiversity aspects when analyzing social-ecological dynamics (Fig. 1.6). Second, the difficulties in the practical application of the SES concept are hindering its use in management plans and actions. Two decades after the creation of the first SES framework (Berkes and Folke 1998), most studies on social-ecological association have a strong theoretical focus and fail in the operationalization of the social-ecological frameworks in management (Partelow, 2018).

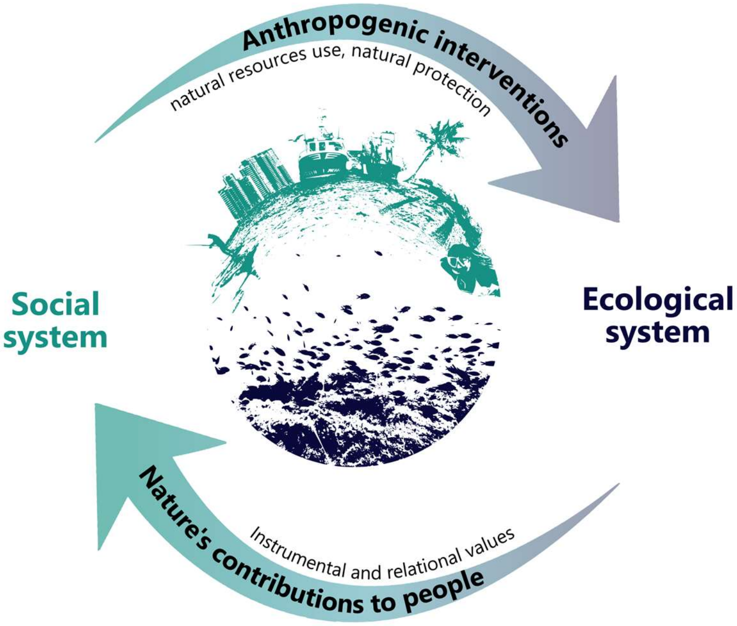


Figure 1.5. Conceptual model of social and ecological components that define social-ecological systems. Modified form Resilience Alliance, 2007

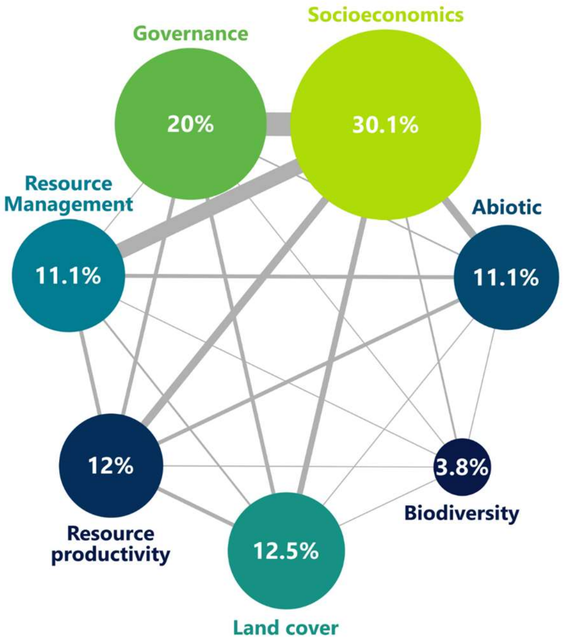
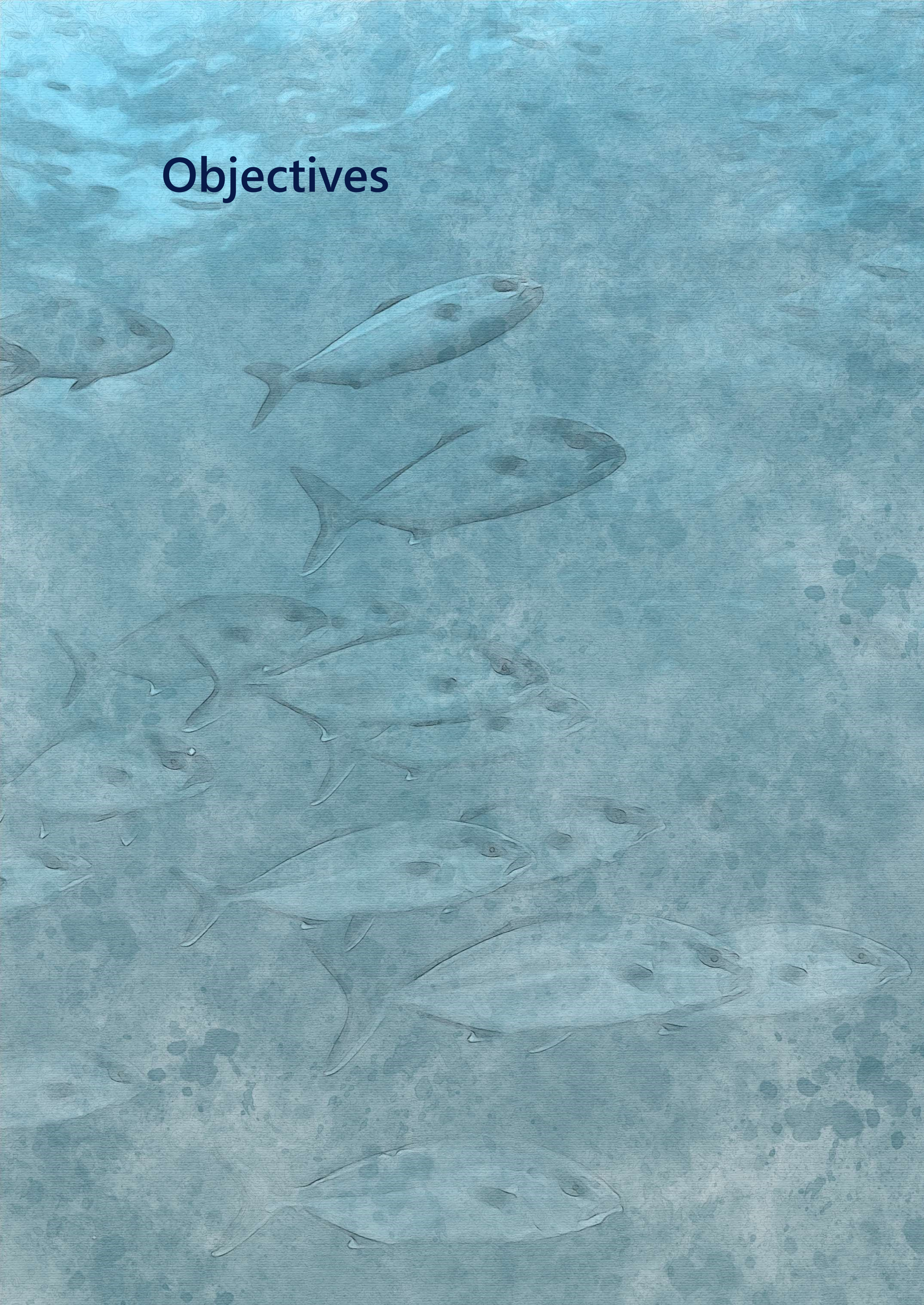


Figure 1.6. Percentage of papers on social-ecological systems attending to the inclusion of the different types of variables, i.e., variables from socioeconomics, governance, resouce management, resource productivity, land cover, biodiversity, and abiotic component.

In the Anthropocene era, we must overcome the above-mentioned challenges for ensuring the future of coastal and marine SES. This thesis advances the understanding of the complex associations that characterize coastal and marine SES to develop integrative management practices that can reduce biodiversity loss and preserve the sustainability of our oceans and seas.

Objectives



Picture: School of Greater amberjack (*Seriola dumerili*) in Fuerteventura (Canary Islands, Spain) by Jose A. Sanabria-Fernandez

2

Objectives

To contribute to the social-ecological knowledge of coastal systems, the overall goal of this thesis is to assess the social-ecological associations of the Spanish coastal and marine systems to identify sustainable management strategies. Because the use of social-ecological approaches to study coastal systems is brand-new, and still in development, this thesis has contributed to establishing the basis for social-ecological studies on the marine coastline. To achieve the overall goal of this thesis, we set three specific objectives:

- **Objective 1.** To develop a methodological approach for defining and identifying coastal and marine SES.
- **Objective 2.** To quantify and assess the marine biodiversity according to the socio-economic and marine environmental characteristics of the coastline.
- **Objective 3.** To detect hotspots of social-ecological vulnerability that require immediate action for increasing their resilience

Each specific objective corresponds to a scientific paper published or in process of publication in international peer-reviewed journals (Fig. 2.1).

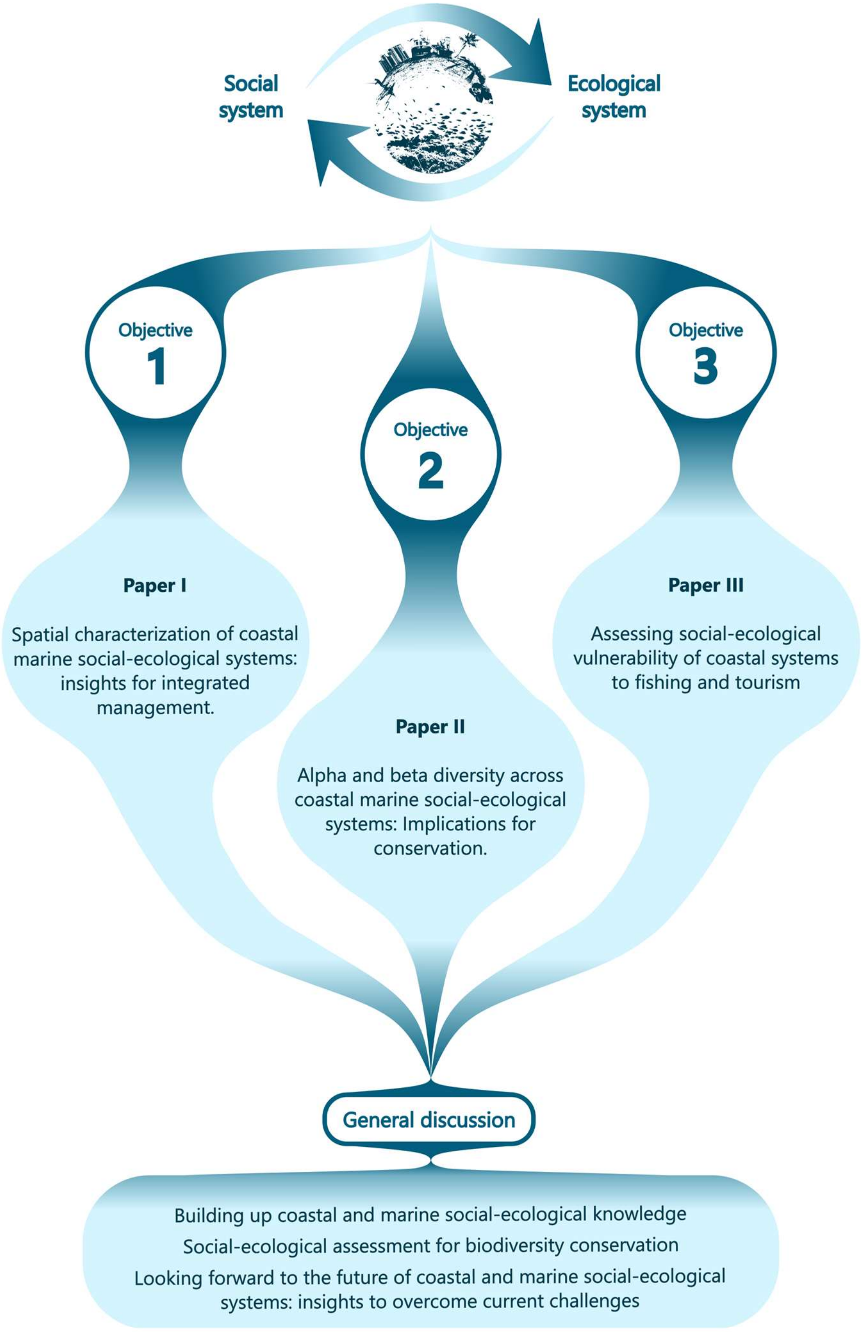
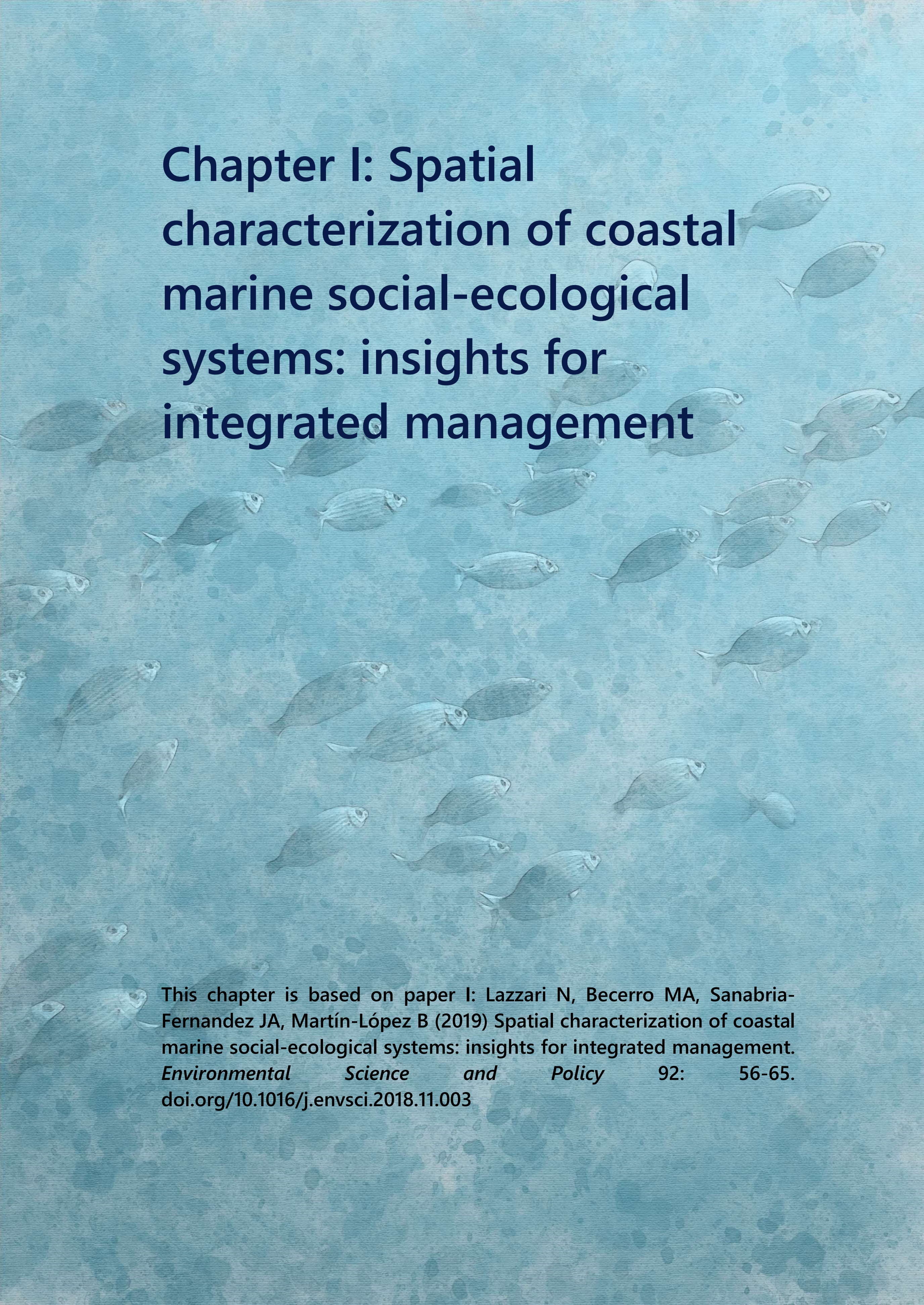


Figure 2.1. Thesis' structure. Vinculation between the objectives of the thesis and the sections of results.



Chapter I: Spatial characterization of coastal marine social-ecological systems: insights for integrated management

This chapter is based on paper I: Lazzari N, Becerro MA, Sanabria-Fernandez JA, Martín-López B (2019) Spatial characterization of coastal marine social-ecological systems: insights for integrated management. *Environmental Science and Policy* 92: 56-65. doi.org/10.1016/j.envsci.2018.11.003

Picture: School of Salema *(Sarpa salpa)* in Tenerife (Canary Islands, Spain) by Natali Lazzari

3

Chapter I: Spatial characterization of coastal marine social-ecological systems: insights for integrated management

Abstract

Understanding the complexity of social-ecological systems is fundamental for achieving sustainability. Historically, humans have benefited from the ecosystem services offered by nature at the same time that natural systems have increasingly changed because of anthropogenic activities. The lack of methods to unveil and understand such associations might hinder the integrated management of coastal marine areas. In our study, we applied a methodological framework used in terrestrial systems to identify and spatially locate the coastal marine social-ecological systems (CMSESs) on the southern Mediterranean Spanish coast. These CMSESs represent areas with similar human-nature associations that result from sharing similar socioeconomic and marine environmental characteristics. We applied several multivariate analyses to identify and characterize these CMSESs. We found the presence of twelve CMSESs that suggest a co-evolution of the social-ecological associations in these areas. Our results highlight the need for integrated coastal planning and management that consider the specific characteristics and conservation challenges of each CMSES. Our study provides evidence that a successful methodological framework to identify and characterize social-ecological systems can be

applied in coastal areas and contribute to integrated management for the sustainability of these fragile systems.

3.1.Introduction

Social-ecological systems are complex adaptive systems in which social and bio-geophysical dimensions interact on multiple temporal and spatial scales (Berkes and Folke, 1998; Liu et al., 2007; Ostrom, 2009). These social-ecological associations point to mutual dependencies between social and ecological components. While human activities such as pollution or habitat protection have an impact on ecological dynamics (e.g., Vitousek et al., 1997), natural processes such as extreme weather events influence the ecosystem services provided to society (Adger, 2005; Liu et al., 2007). Understanding the associations between ecological and social systems is particularly relevant in achieving sustainability (Glaser et al., 2012).

Coastal systems support the livelihood of a large and growing proportion of the world's human population (Agardy et al., 2005). Over centuries, human societies have benefited from the ecosystem services provided by coastal marine systems such as food from fisheries, regulation of natural hazards (e.g., tsunamis), and recreational or aesthetic experiences (Liquete et al., 2013a; Martínez et al., 2007). However, coastal areas are also facing significant coastal erosion, pollution, and biodiversity loss (Cloern et al., 2016; Vitousek et al., 1997), which in turn have jeopardized the ecosystem services provided (Serrao-Neumann et al., 2016). To revert the degradation of coastal ecosystem services through more sustainable management actions, it is necessary to understand the complex associations that characterize social-ecological systems (de Andrés et al., 2017). The number of studies that have sought to understand social-ecological associations has increased in the last decade (Binder et al., 2013; Rissman and Gillon, 2017), particularly in coastal areas (e.g., Álvarez-Romero et al., 2011; Ban et al., 2013; Cinner et al., 2009). However, there is no empirical evidence on how these associations are expressed spatially, i.e., the spatial configuration of coastal marine social-ecological systems (CMSESs). Although some methodological approaches have been suggested for mapping coastal ecosystem services (Sousa et al., 2016) or human impacts on coastal and marine systems (Ban et al., 2010; Halpern et al., 2009), few studies have developed methodological tools to spatially represent CMSESs, particularly at regional scales (Mahboubi et al., 2015). The lack of methodological developments to spatially characterize social-ecological associations at the regional scale is considered a major drawback of using the social-ecological system framework in management (Hanspach et al., 2016; Martín-López et al., 2017). In fact, the lack of empirical evidence on the spatial representation of CMSES can lead to their mismanagement (Liu et al., 2007; Rissman and Gillon, 2017).

In our study, we aim to spatially identify and characterize the social-ecological associations within CMSES by analysing the marine environmental and socioeconomic characteristics of coastal marine areas. We tested a methodological approach to identify and characterize CMSESs on the southern Mediterranean Spanish coast.

3.2.Materials and methods

3.2.1.Study area

The study area is located on the Mediterranean coast of Andalusia in southern Spain (Fig. 4.1). The 500 km-long coastal area investigated in our study spans over 41 littoral municipalities belonging to four Andalusian provinces (Cadiz, Malaga, Granada, and Almeria). The Andalusian shoreline includes a wide variety of land and sea uses, from natural protected areas such as the Natural Park of the Strait (Cadiz) to intensively managed lands and fishing areas such as the greenhouses of El Ejido and the littoral area of La Garrucha, respectively (both in Almeria; Fig. 3.1). Environmentally, the Mediterranean coast of Andalusia is also highly variable because the Mediterranean Sea is connected to the Atlantic Ocean in the west by the Strait of Gibraltar (Coll et al., 2010). Indeed, this region of the Mediterranean has unique oceanographic characteristics with the coldest, least saline, and most productive waters of the entire Mediterranean Sea due to the mixing of Atlantic and Mediterranean waters (Minas et al., 1991). In addition, the irregular underwater geography of the western Mediterranean Sea, with numerous canyons, anticyclonic areas, and an important shelf extension, promotes the existence of coastal upwellings that support high productivity

(Pinardi et al., 2006; Sarhan et al., 2000). As a result, the marine area investigated in our study includes a wide variety of marine ecosystems, such as rocky reefs, seagrasses, soft bottoms and deep coral reefs. Due to these characteristics, the Mediterranean Sea is recognized as one of the world's marine biodiversity *hotspots* (Coll et al., 2010; Myers et al., 2000).

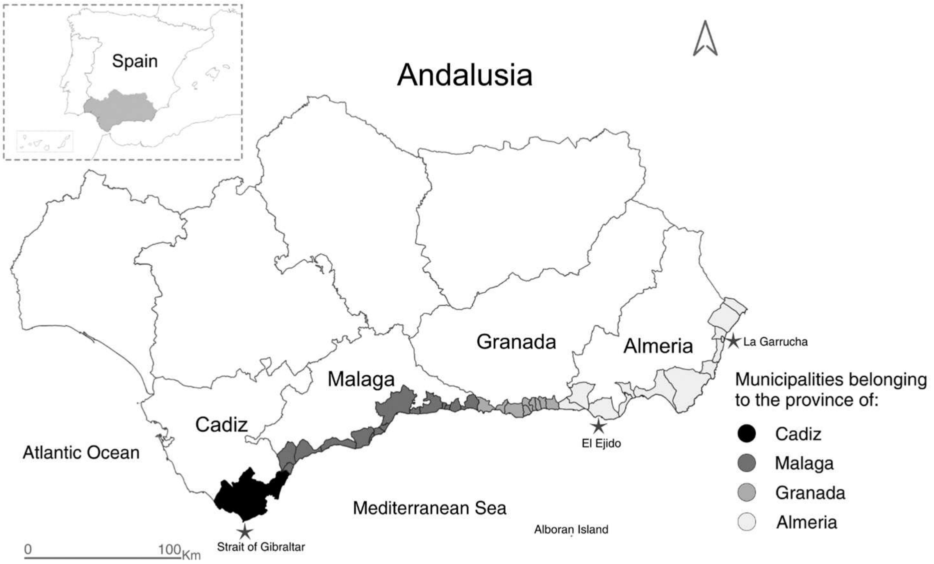


Figure 3.1. Map of the study area on the Mediterranean coast of Andalusia. The map illustrates the geographical location of the coastal municipalities, which belong to the four Andalusian provinces of Cadiz (5 municipalities), Malaga (14 municipalities), Granada (9 municipalities), and Almeria (13 municipalities).

As in other areas of the world, rural Andalusian populations decrease as urban populations grow, particularly in coastal areas (Collantes and Pinilla Navarro, 2011; Garcia-Llorente et al., 2015). The Mediterranean coast of Andalusia hosts 9.70% of the Spanish population, which is almost five million inhabitants distributed throughout 4 provinces with a total surface of 36,167 km2. The average unemployment rates exceed 10% in this area, with that in Cadiz reaching a peak of 15%. Almeria is the province with the highest percentage of illiteracy (2.80%), and Granada has the highest percentage of people with a university degree (16.10%). In all of these provinces, the tertiary sector (i.e., building, transport, and services) and the primary sector (i.e., agriculture, fishing, and livestock) contribute the highest and lowest income, 77.60% and 6.60% of the Andalusian Gross Domestic Product, respectively. The fishing sector employs almost 4,500 inhabitants. The province of Cadiz has the highest number of professional boats per kilometer of coast and the largest fishermen's guild, followed by Malaga, Almeria, and Granada.

The current rise of the human population and urbanization of coastal areas (de Andrés et al., 2017) together with the over-exploitation of fisheries in the Mediterranean coast of Andalusia promote biodiversity loss, pollution, and the degradation of important habitats such as rocky reefs, seagrasses, and estuaries (Coll et al., 2010).

3.2.2.Data collection

Following the methodological approach developed by Martín-López et al. (2017) to identify terrestrial social-ecological systems, we collected marine environmental and socioeconomic data to identify and characterize the marine environmental and socioeconomic spatial classes that were homogeneous within but distinct among the social-ecological systems (Fig. 3.2). The marine environmental information was extracted from the satellite database Bio-ORACLE (Assis et al., 2018). To obtain the marine environmental data, we extracted the values of nine variables from ocean pixels contiguous to the coastline with a 9.2 × 9.2 km resolution (the maximum resolution of the Bio-ORACLE database) (see Fig. S1 in Appendix for Chapter I). We selected nine marine environmental variables that are essential for marine biodiversity (Stuart-Smith et al., 2013) (see Table S1 in Appendix for Chapter I): inorganic carbon (calcite concentration), primary productivity (minimum chlorophyll a, and mean chlorophyll a), nutrients (nitrate and phosphate concentrations), salinity, and sea surface temperature (maximum SST, mean SST and SST range). We averaged the pixel values for each municipality for each marine environmental variable to obtain a single marine environmental value per municipality.

We collected the socioeconomic information from three public databases: SIMA (Andalusian Multi-Territorial Information System, 2018), SEPE (Public Service State Employment, 2018), and MAPA (Ministry of Agriculture, Fisheries and Food, 2018). We collected socioeconomic information for the 41 municipalities located on the Mediterranean coastline of Andalusia. We selected the municipality as the most suitable organizational level to collect socioeconomic data because it is the most detailed administrative unit at which official statistics exist (Martín-López et al., 2017). We collected 24 socioeconomic variables at the municipal scale (see Table S2 in Appendix for Chapter I). The socioeconomic information encompassed variables on demography, economic status, land use, fishing activity, and environmental protection. The demographic variables included population density, age (percentage of people younger than 25 years old and percentage of people older than 65 years old), and education level (percentage of people with university degree and percentage of illiterate people). The variables regarding economic status included income, the percentage of people employed in the primary, secondary, and tertiary economic sectors, the percentage of unemployed people, and the number of tourist accommodations per kilometer of coast. The variables conveying information on land use included information on natural surfaces (percentages of mountains, rivers, lakes, non-agricultural, and non-productive surfaces), agricultural surfaces (percentages of meadows, crops, and fallows), and livestock per Ha. We included land use information because land use changes in recent decades (intensification and rural abandonment) have been the main direct drivers of the changes in Spanish and worldwide ecosystems (MAGRAMA, 2014; Pereira et al., 2012). The fishing activity variables included tons of catches, the number of fishing vessels per kilometer of coast, and the percentage of people employed in the fishery sector. Finally, we also considered the level of environmental protection by including two variables: the percentages of land and sea surface covered by terrestrial and marine protected areas, respectively.

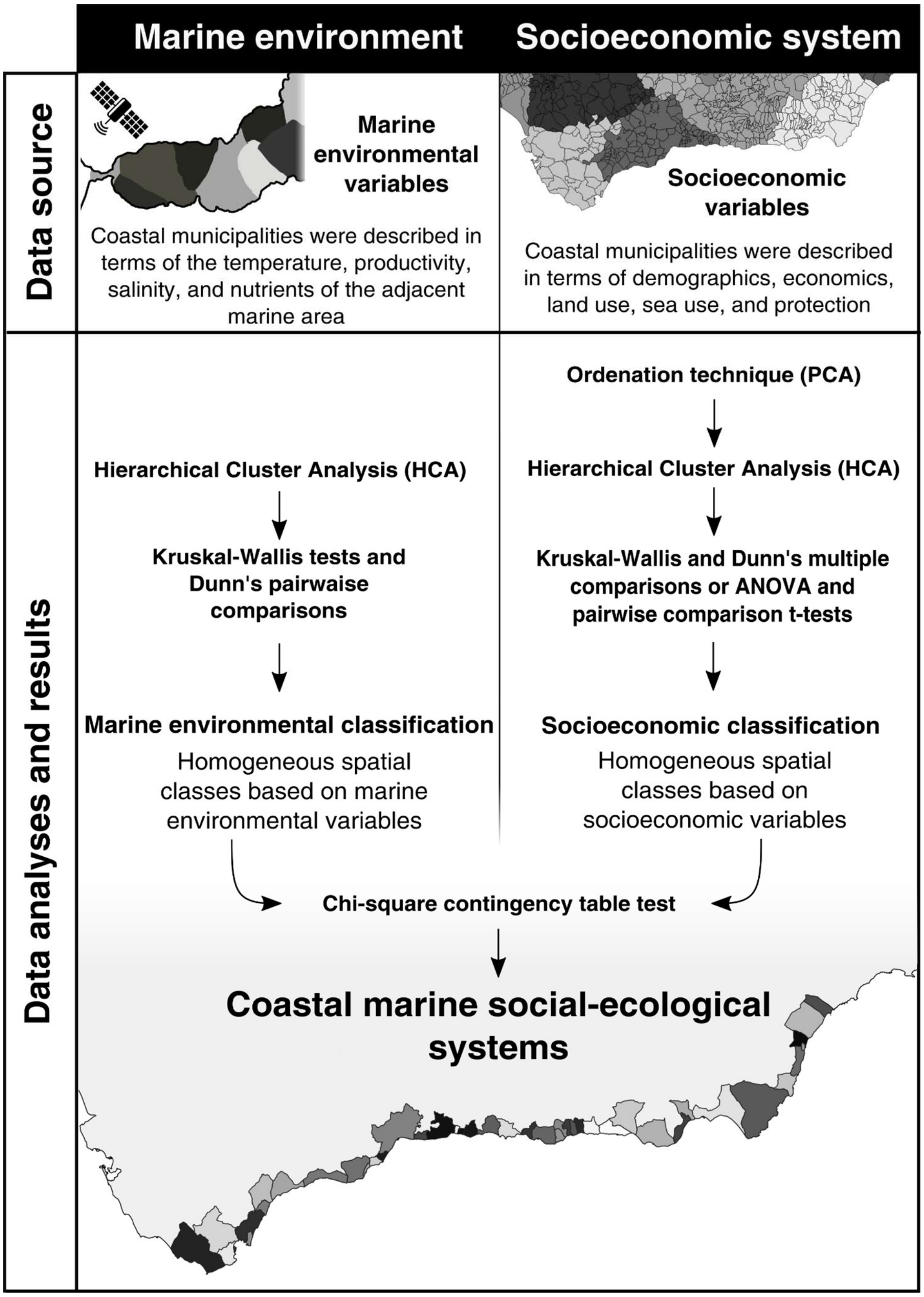


Figure 3.2. Methodological approach used to identify and characterize the coastal marine social-ecological systems (CMSESs) in Andalusia. Adaptation from Martín-López et al. (2017).

3.2.3.Data analysis

We followed a combination of two analytical approaches with the marine environmental variables and socioeconomic variables to characterize the Andalusian CMSESs (Fig. 3.2). First, we performed a principal component analysis (PCA) with varimax rotation on the socioeconomic data to simplify the dimensions of the socioeconomic variables and to unveil the dominant relationships among them. We selected the PCA components with an eigenvalue higher than 1, i.e., the Kaiser criterion (Kaiser, 1960). Second, we carried out two hierarchical cluster analyses (HCA), first HCA with the standardized marine environmental variables and second HCA with the socioeconomic PCA components, to identify homogenous marine environmental and socioeconomic classes, respectively. We used Euclidean distance and Ward's method as agglomerative hierarchical techniques (Ward, 1963). Third, we conducted ANOVA and Kruskal-Wallis tests to test for differences in the considered variables (see Table S1 and S2 in Appendix for Chapter I) among the multiple classes obtained by the marine environmental and socioeconomic HCAs. When the ANOVA and Kruskal-Wallis tests were significant (p-value < 0.05), we used post hoc pairwise comparisons t-tests and Dunn's multiple comparisons tests, respectively, to assess the differences between classes. The Shapiro-Wilk test was initially used to check for normality for all the marine environmental and socioeconomic variables used.

Finally, we performed a Chi-squared contingency table analysis to explore the level of association between the identified marine environmental and socioeconomic classes and, thus, to identify the CMSESs. To graphically visualize the differences among CMSESs, we conducted a non-metric multidimensional scaling (nMDS) based on Euclidean similarity, taking its stress value as an indicator of the goodness of representation. Radar charts were used to represent the influence of the socioeconomic and marine environmental variables on each CMSES. We used R software (R Core Team, 2015) to conduct the statistical analyses.

3.3.Results

3.3.1.Marine environmental classifications

Through the HCA, we identified five marine environmental classes (MECs) (Fig. 3.3a). Whereas the municipalities of MEC2 were characterized by the highest concentrations of nitrate and phosphate (2.02 mol/m^3 and 0.18 mol/m^3, respectively) (Table 3.1), MEC3 was characterized by the highest values of calcite (3.47e-4 mol/m^3), minimum chlorophyll a (0.68 mg/m^3), and mean chlorophyll a (1.99 mg/m^3) (Table 3.1). The municipalities in MEC5 were characterized by the highest values of maximum SST (25.55 ºC), mean SST (19.18 ºC), SST range (11.21 ºC) and salinity (37.10 PSS) (Table 3.1). This class also had the lowest values of the remaining marine environmental variables, i.e., calcite, mean chlorophyll a, minimum chlorophyll a, nitrate, and phosphate. Finally, MEC1 and MEC4, which were geographically located between MEC2 and MEC5 (Fig. 3.3a), had intermediate values of all marine environmental variables. The Kruskal-Wallis tests showed significant differences in all marine environmental variables among these classes (Table 3.1).

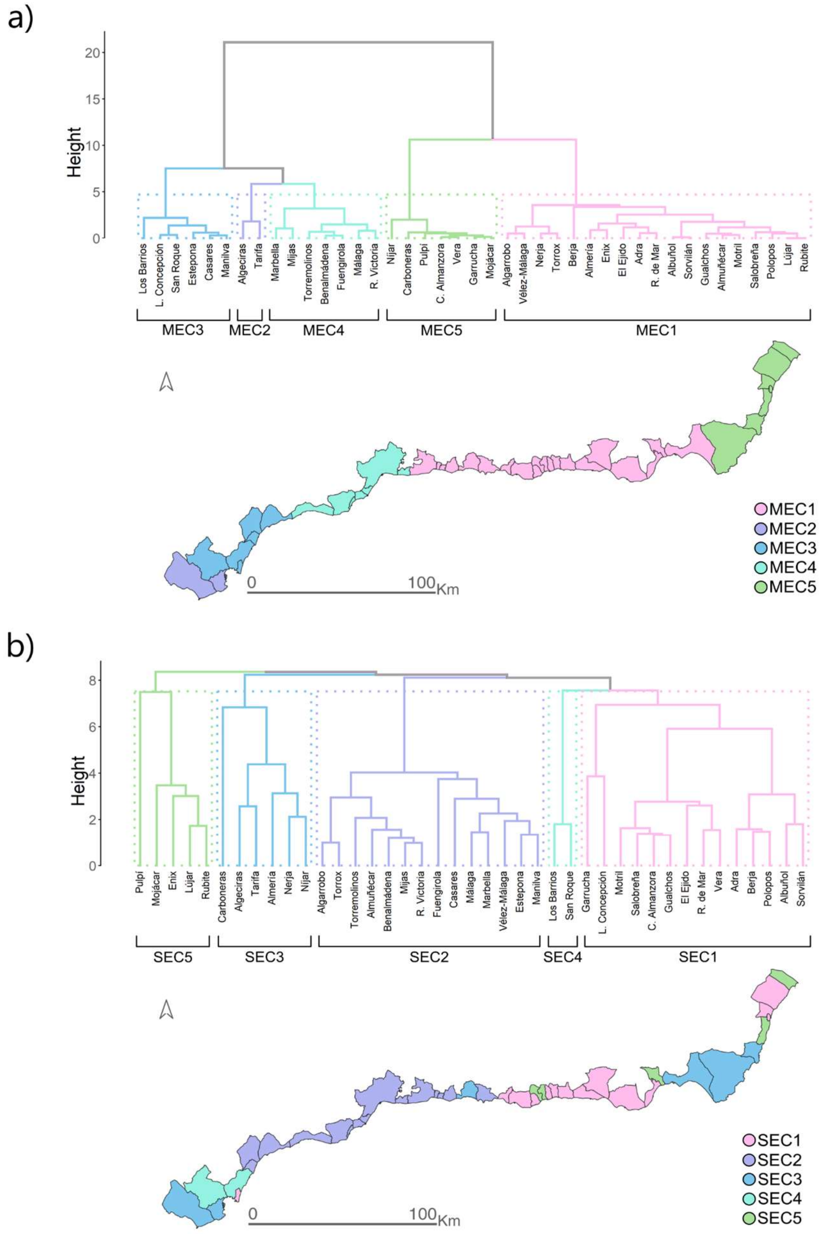


Figure 3.3. Dendrogram and map with the municipalities included in each (a) marine environmental class (MEC) and (b) socioeconomic class (SEC).

Variables	MEC1	MEC2	MEC3	MEC4	MEC5	X^2
Mean calcite (mol/m^3)	2.86E-04^{a}	2.98E-04^{a,b}	**3.47E-04^{a}**	2.95E-04^{a}	1.28E-04^{b}	21.58**
Mean chlorophyll a (mg/m^3)	0.87^{a,b}	0.63^{a,b}	**1.99^{c}**	1.19^{a,c}	0.35^{b}	34.31**
Minimum chlorophyll a (mg/m^3)	0.29^{a}	0.35^{a,b}	**0.68^{b}**	0.58^{b}	0.16^{a}	34.50**
Mean nitrate (mol/m^3)	1.42^{a,b}	**2.02^{a,c}**	1.96^{c}	1.75^{a,c}	1.15^{b}	35.16**
Mean salinity (PSS)	36.92^{a,b}	36.34^{a,c}	36.47^{c}	36.77^{a,c}	**37.10^{b}**	35.16**
Maximum SST (°C)	24.38^{a,b}	21.79^{a,c}	22.02^{c}	23.19^{a,c}	**25.55^{b}**	35.42**
Mean SST (°C)	18.67^{a,b}	18.18^{a,c}	17.76^{c}	18.35^{a,c}	**19.18^{b}**	36.34**
Range SST (°C)	9.72^{a,b}	6.39^{a,c}	7.19^{c}	8.32^{a,c}	**11.21^{b}**	35.52**
Mean phosphate (mol/m^3)	0.14^{a,b}	**0.18^{a,c}**	0.17^{c}	0.16^{a,c}	0.11^{b}	35.47**

Table 3.1. Mean values of the marine environmental variables in each marine environmental class (MEC) and X^2 statistic for the significant differences among the MECs. The MECs sharing superscript letters (a, b, or c) do not differ (Dunn's multiple comparison tests after Bonferroni correction). The bold values point to the MEC with the highest mean value for each variable. ** $p < 0.01$

3.3.2. Socioeconomic classifications

The first eight components of the PCA presented eigenvalues higher than 1 (i.e., Kaiser criteria) and explained 78% of the variance in the socioeconomic data (see Table S3 in Appendix for Chapter I). The first socioeconomic component, PCA1 (13% of the variance), represented by its positive scores those municipalities with high population densities and whose populations have university degrees and work in the tertiary sector. In contrast, the negative scores of PCA1 represented those municipalities with high rates of illiterate people and with meadows. PCA2 (12%) had a gradient based on age, with those municipalities representing people younger than 25 with positive scores and those with people older than 65 with negative scores. PCA3 (11%) was associated with the land uses of rivers and lakes, non-productive surfaces, and fallows and with people mainly employed in the primary sector. PCA4 (11%) was associated with high rates of protected surfaces, both terrestrial and marine. PCA5 (10%) encompassed those variables representing the fishing activity (catches, fishing vessels, and fishers). PCA6 (9%) was associated with high annual income and with a population employed in the secondary sector. PCA7 (7%) represented those municipalities with high rates of unemployment and non-agricultural surfaces. Finally, PCA8 (6%) was associated with tourism activity.

By using these eight PCA components in the HCA, we identified five socioeconomic classes (SECs) (Fig. 3.3b; Table 3.2). The municipalities within SEC1 and SEC2 had the highest population densities (235.09 and 757.48 inhabitant km-2, respectively), but they differed in education level. Whereas municipalities within SEC1 had the highest percentage of illiterate people (3.67%), the municipalities within SEC2 had the highest rate of people with university-level education (14.04%). In addition, the municipalities within SEC2 were also characterized by the lowest percentage of people employed in the primary sector (2.30%). In contrast, SEC1 and SEC5 represented those municipalities with the highest percentage of the population employed in the primary sector (12.89% and 32.21%, respectively). SEC1 and SEC5 had other commonalities, as both classes represented those municipalities with the highest percentage of fallow land use (13.77% and 14.42%, respectively) (Table 3.2). SEC1 also had the highest percentage of surface with non-productive and non-agricultural land uses (6.67%, 15.06%, respectively) (Table 3.2).

Type	Variables	SEC1	SEC2	SEC3	SEC4	SEC5	*F*	X^2
Demographic	Population density (Ln)	5.46^{a}	**6.63^{a}**	5.21^{a,b}	4.78^{a,b}	3.22^{b}	6.11**	
	Illiterate people (%)	**3.67^{a}**	2.06^{a,b}	2.68^{a,b}	2.15^{a,b}	0.37^{b}		15.57**
	People with a university degree (%)	7.51^{a}	**14.04^{b}**	11.17^{a,b}	9.16^{a,b}	7.78^{b}	3.14*	
	People younger than 25 (%)	28.19^{a}	26.06^{a,b}	27.22^{a,b}	**29.31^{a,b}**	17.18^{b}		13.47**
	People older than 65 (%)	14.43	16.61	15.12	12.88	23.14		9.81*
Economic	People employed in primary sector (%)	12.89^{a}	2.30^{b}	6.41^{a,b}	0.57^{a,b}	**32.21^{a}**		16.44**
	People employed in secondary sector (%)	2.79^{a}	3.66^{a,b}	4.31^{a,b}	**15.45^{b}**	4.30^{a,b}		9.77*
	People employed in tertiary sector (%)	15.83	22.43	26.11	22.51	20.13	2.37	
	People unemployed (%)	9.87^{a}	9.48^{a}	10.42^{a}	**12.35^{a}**	5.80^{b}	7.24**	
	Annual income per inhabitant (Ln)	6.92^{a}	7.32^{b}	7.01^{a,b}	**7.53^{b}**	7.18^{a,b}	6.11**	
	Tourist accommodations (N/km)	0.21	0.94	0.26	0.08	0.12		9.74*
Land use	Mountains (%)	11.18^{a}	0.05^{b}	24.72^{a}	**57.23^{a}**	17.36^{a}		28.22**
	Meadows (%)	22.24	15.99	9.97	16.50	29.99		7.61
	Non-productive (%)	**6.67^{a}**	0.33^{b}	3.78^{a,b}	3.98^{a,b}	4.24^{a,b}		24.76**
	Non-agricultural (%)	**15.06^{a}**	0.89^{b}	8.01^{a,b}	14.14^{a,b}	5.90^{a,b}		23.32**
	Rivers and lakes (%)	1.76^{a}	0.01^{b}	1.28^{a,b}	**2.67^{a}**	2.39^{a}		28.15**
	Crops (%)	21.02	16.13	7.72	3.23	12.48		6.73

Type	Variables	SEC1	SEC2	SEC3	SEC4	SEC5	*F*	X^2
	Fallow (%)	13.77^{a}	0.96^{b}	$0.36^{b,c}$	$0.60^{a,b}$	$\mathbf{14.42^{a,c}}$		24.86**
	Livestock (individual/Ha)	0.06	0.07	0.10	0.16	0.23		2.84
Fishing activity	Catches (N/km)	3.92	4.00	6.78	0.00	0.00		5.032
	Fishing vessels (N/km)	1.59	0.89	0.51	0.00	0.00		4.53
	Fishers (%)	0.13	0.08	0.89	0.00	0.00		7.02
Protection	Land protected area (%)	1.08^{a}	1.54^{a}	$\mathbf{53.08^{b}}$	$46.31^{a,b}$	0.00^{a}		26.07**
	Marine protected area (%)	0.00^{a}	0.11^{a}	$\mathbf{9.02^{b}}$	0.00^{a}	0.00^{a}		35.11**

Table 3.2. Mean values of the socioeconomic variables in each socioeconomic class (SEC), *F-value*, and X^2 statistic for the significant differences among the socioeconomic classes. The SECs sharing superscript letters (a, b or c) do not differ (pairwise comparison t-tests or Dunn's multiple comparison tests after Bonferroni correction). The bold values point to the SEC with the highest mean value for each variable. * $p<0.05$, ** $p<0.01$

SEC3 was represented by those municipalities with the highest rates of terrestrial and marine protected areas (53.07% and 9.02%, respectively) (Table 3.2). Finally, SEC4 was characterized by distinctive demographic, economic, and land-use variables. Demographically, the municipalities within SEC4 had the highest percentage of people younger than 25 years old (29.31%). Economically, SEC4 had the highest annual income (1863.11 €) and the highest percentage of people employed in the secondary sector (15.45%). However, this class also had the highest rate of unemployment (12.35%). Regarding land uses, SEC4 was characterized the highest percentage of surface belonging to mountains (57.23%) and rivers and lakes (2.67%) (Table 3.2). Regarding the variables for fishing activity, we did not find differences among the SECs, although SEC4 and SEC5 showed no activity (Table 3.2).

3.3.3. Characterization of the CMSESs

We found a significant association between the socioeconomic and marine environmental classes ($\chi 2 = 47.27$; $p < 0.001$), which resulted in twelve CMSES (Fig. 3.4, Fig. 3.5). However, MEC2 and MEC4 were only associated by one SEC, i.e., SEC3 and SEC2, comprising CMSES2 and CMSES5, respectively, and the remaining three marine environmental classes were associated with different socioeconomic classes. CMSES2 was geographically located in the western region of the Andalusian coastline (Fig. 3.5b) and was characterized by high levels of nitrates and phosphates (i.e., MEC2) and a high representation of terrestrial and marine protected areas (i.e., SEC3) (Fig. 3.6b). CMSES5 was located in the central area of the Malaga coastline (Fig. 3.5b) and was mainly characterized by municipalities with high population densities and a high rate of people with university-level education (SEC2; Table 3.2). Environmentally, CMSES5 had intermediate values of all marine environmental variables that comprised the marine environmental class of MEC4 (Fig. 3.6e).

The other marine environmental class that had intermediate values for all variables (MEC1) was associated with four different socioeconomic classes (SEC1, SEC2, SEC3, and SEC5), comprising CMSES1, CMSES9, CMSES10, and CMSES11, respectively (Fig. 3.4). All of these CMSESs were characterized by the same marine environmental variables, but they actually differed in socioeconomic characteristics and thus represented different coastal areas of Malaga, Granada, and Almeria (Fig. 3.5b). Whereas CMSES9 and CMSES10 were located in the eastern part of Malaga, CMSES1 and CMSES 11 were distributed throughout Granada and in western Almeria. In addition, it is remarkable that while CMSES1 was broadly spread throughout these provinces, CMSES11 appeared in very few areas (Fig. 3.5b). This difference relied on the socioeconomic differences: whereas CMSES11 represented municipalities with a high rate of employment in the primary sector (Fig. 3.6k), CMSES1 represented those municipalities with a high percentage of land surface with non-productive and non-agricultural land uses (Fig. 3.6a). The differences between CMSES9 and CMSES10 in eastern Malaga also depended on socioeconomic aspects. Whereas CMSES9 had similar characteristics to CMSES5 in terms of a high population density and a high percentage of people with university-level education (Figs. 2.6i and 2.6e), CMSES10 had a high percentage of both terrestrial and marine protected areas (Fig. 3.6j).

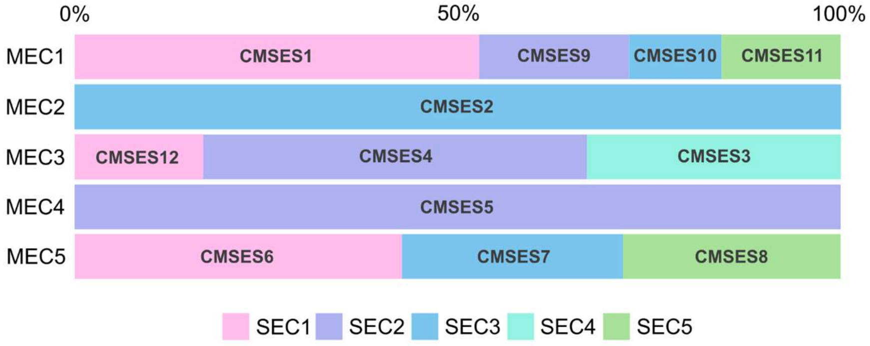


Figure 3.4. Bar diagram representing the associations among the marine environmental (MEC) and socioeconomic (SEC) classes and the consequent CMSESs. ($\chi2 = 47.27$; $p < 0.001$)

The marine environmental class of MEC3, represented by the eastern region of Cadiz and western Malaga, was characterized by high levels of primary production (i.e., chlorophyll a). MEC3 was associated with three socioeconomic classes (SEC1, SEC2, and SEC4) representing three social-ecological systems: CMSES12, CMSES4, and CMSES3, respectively. Each of these social-ecological systems was distinctively located in different regions: CMSES12 represented the unique municipality in Cadiz bordering Gibraltar (a British overseas territory), CMSES3 represented other municipalities in Cadiz, and CMSES4 represented municipalities in Malaga (Fig. 3.5b). The administrative differences in the municipalities entailed different socioeconomic characteristics (Fig. 3.6). Whereas CMSES3 was characterized by the highest rate of young people and people working in the secondary sector (Fig. 3.6c), CMSES 4 had a high population density and percentage of people university-level education (Fig. 3.6d). In contrast, CMSES12 was characterized by a high rate of illiterate people (Fig. 3.6l).

The eastern region of the Andalusian coastline was environmentally characterized by the highest values of SST and salinity and the lowest productivity, which were characteristic features of the marine environmental class of MEC5. Despite the environmental similarities in the region, the socioeconomic differences entailed multiple CMSESs. MEC5 was associated with the socioeconomic classes of SEC1, SEC3, and SEC5, representing CMSES6, CMSES7, and CMSES8 (Fig. 5). Whereas CMSES6 had a high percentage of illiterate people and a high percentage of land surface with non-productive and non-agricultural land uses (Fig. 3.6f), CMSES8 was characterized by a high percentage of people working in the primary sector and a high percentage of fallow surface (Fig. 3.6h). Both CMSES6 and CMSES8 had a small percentage of terrestrial and marine protected areas. In contrast, CMSES7 was characterized by a high percentage of terrestrial and marine protected areas (Fig. 3.6g).

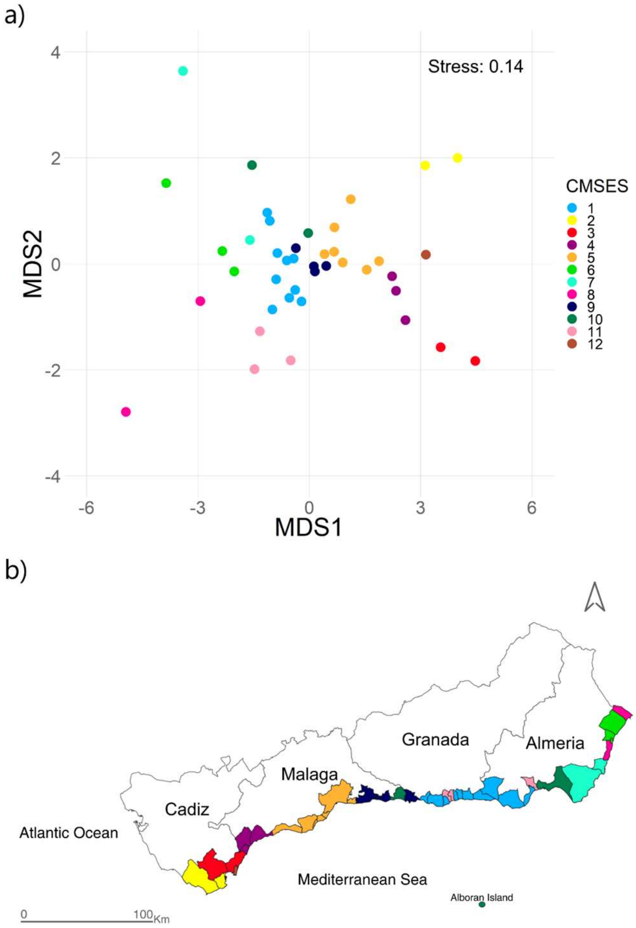


Figure 3.5. (a) Two-dimensional nMDS (nonmetric multidimensional scaling) of the coastal marine social-ecological systems (CMSESs) based on socioeconomic and marine environmental characteristics. (b) Map with the geographic location of each CMSES.

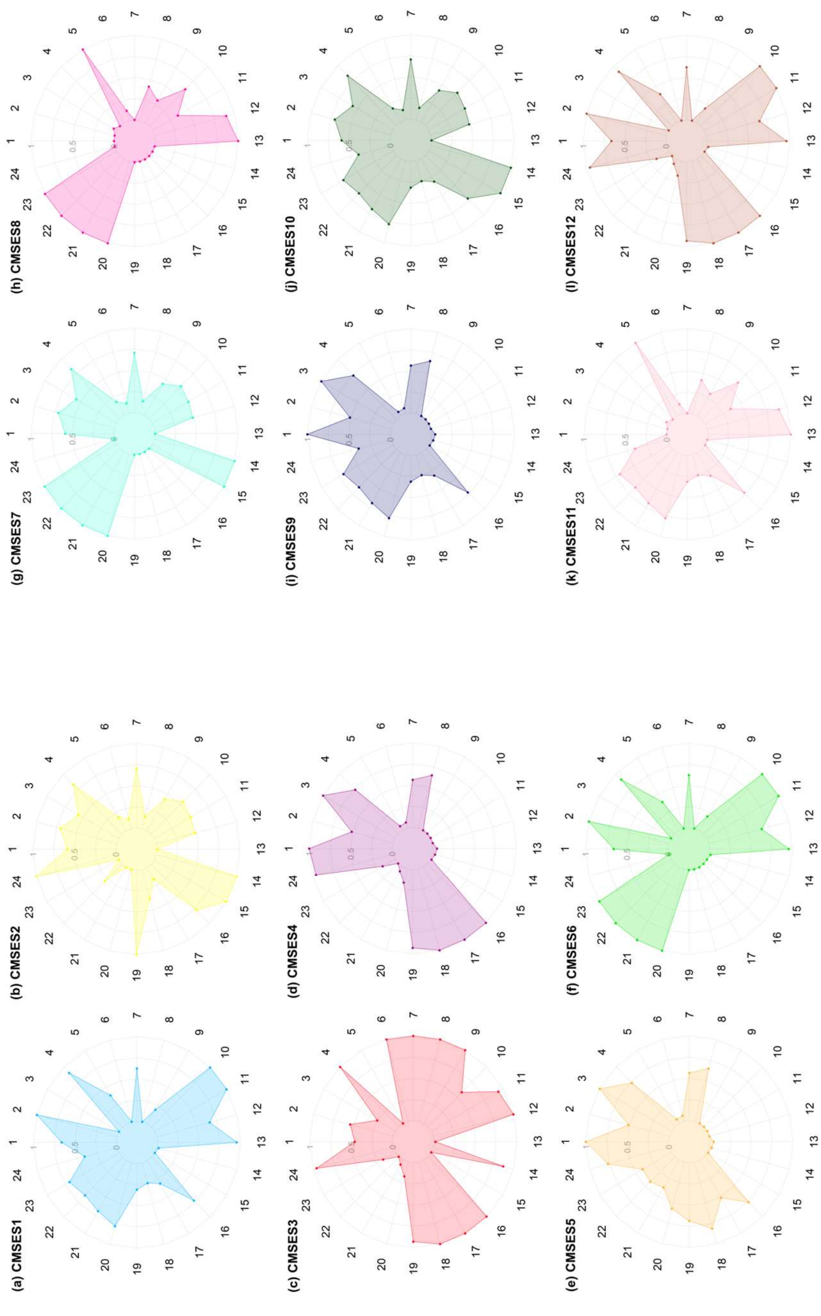


Figure 3.6. Socioeconomic and marine environmental variables that characterize the CMSESs from (a) to (l). The peripheral numbers from 1 to 24 are codes for the socioeconomic and marine environmental variables: (1) population density, (2) illiteracy, (3) people with a higher education, (4) people younger than 25, (5) people employed in the primary sector, (6) people

employed in the secondary sector, (7) people who are unemployed, (8) annual income per inhabitant, (9) mountains, (10) non-productive, (11) non-agricultural, (12) river and lakes, (13) fallow, (14) land protected area, (15) marine protected area, (16) mean calcite, (17) mean chlorophyll a, (18) minimum chlorophyll a, (19) mean nitrate (20) mean salinity, (21) maximum SST, (22) mean SST, (23) SST range, and (24) mean phosphate.

3.4.Discussion and conclusions

Through the application of a methodological framework used formerly in terrestrial systems (Martín-López et al., 2017), this study spatially identified twelve CMSESs. Each CMSES represented a homogenous, although geographically continuous or discontinuous, area of varying sizes characterized by similar associations between the socioeconomic and marine environmental characteristics. Therefore, our study provides a methodological framework to characterize and spatially locate the social-ecological systems in coastal marine systems. Far from trivial, accurate spatial localization of social-ecological systems is one of the main limitations on using the framework of social-ecological systems in marine management (de Andrés et al., 2017).

Despite the capacity of the suggested methodological approach to identify CMSESs, we should note some of its limitations. First, future studies seeking to improve integrated management will benefit from taking into account biological information such as species richness, abundance, biomass or functional biodiversity (Micheli and Halpern, 2005). Because local biodiversity results from numerous factors, including local environmental conditions, we believe that the identified CMSESs might also differ in biodiversity. For example, Bermejo et al. (2015) identified three subregions of macrophyte diversity in the western Mediterranean that were closely related to marine environmental variables. The CMSESs identified in this study perfectly fit within the biogeographical regions described by Bermejo et al. (2015). The CMSESs that comprised the marine environmental classes of MEC1, MEC2, and MEC3 (i.e., CMSES1-4 and CMSES 9-12; Fig. 3.4) matched the biogeographic region of eastern Alboran. CMSES5 matched the biogeographic region of central Alboran. The CMSESs encompassing the marine environmental class of MEC5 (i.e., CMSES 6-8; Fig. 3.4) matched the biogeographic region of western Alboran. The environmental overlap between both studies evidences differences in the marine macrophyte composition across the identified CMSESs.

Second, the use of municipal statistics does not account for the different governance that occurs due to different policies at the province level. However, the resulting CMSESs showed that the association between marine environmental and socioeconomic characteristics can be the result of government processes at the provincial scale because the identified CMSESs perfectly fit within the borders of the provinces of Cadiz and Malaga and Malaga and Granada. Despite the differences in the CMSESs between provinces and within each province, the Andalusian Strategy for Integrated Coastal Zone Management, resulting from the application of the EU Recommendation on Integrated Coastal Zone Management Marine (2002/413/EC), provides the same legal guidelines for all of Andalusia. This research shows that different CMSESs would benefit from considering their marine environmental and socioeconomic similarities and differences in the policies and management of the coastal marine zones.

We identified twelve CMSESs that conformed to the intermediate areas between provinces and municipalities, e.g., the CMSESs reflected important differences and similarities within and between provinces and municipalities. The specific marine environmental and socioeconomic factors behind the similarities and differences between CMSESs are essential to designing and using management measures and to policy-making decisions. For example, as CMSES2, CMSES3, and CMSES12 were situated in the province of Cadiz, their management relies on the ICZM and the recently approved 'Program for the Coastal Management of the Cadiz province' (July 24th, 2018). However, these CMSESs required distinctive management actions based on their social-ecological characteristics.

CMSES3 and CMSES12 shared the same marine environmental characteristics, whilst CMSES2 differed from them by both marine environmental and socioeconomic characteristics. The marine environmental differences can be explained by the fact that CMSES2 was located in the Strait of Gibraltar, where the Atlantic Ocean connects to the Mediterranean Sea (Coll et al., 2010), and the mix of both waterbodies leads to unique biophysical characteristics, i.e., high concentration of nutrients, low SST, and low salinity (Minas et al., 1991). In contrast, CMSES3 and CMSES12, together with CMSES4 in western Malaga, were environmentally characterized by high productivity and a low SST, which can be explained by a quasi-permanent upwelling region in this area (Navarro et al., 2011).

Socioeconomically, CMSES3 and CMSES12 face different challenges. For example, management actions directed to develop education programs may result in increased awareness about the importance of the coast and the marine systems in CMSES12, which has a low percentage of protected areas and the highest percentage of illiterate people. In contrast, a potential future challenge for CMSES3 might be dealing with human pressure, as this is the CMSES with the highest percentage of young people. These examples show how the classification of CMSESs can support the design of management measures and policies that effectively target the social-ecological realities at local and regional scales.

Furthermore, our results also showed that the design of management programs at the province level might be counterproductive because some CMSESs are located across borders or because of the diversity of CMSESs within a province. As an illustration of CMSESs located across provinces, we found four CMSESs that overlap borders: CMSES1 and CMSES11 that comprise municipalities in Granada and Almeria, CMSES9 in Malaga and Granada, and CMSES10 in Malaga and Almeria. These four CMSESs shared the same marine environmental characteristics, as they were influenced by the northwestern upwelling, but they clearly differed in their socioeconomic characteristics (i.e., population density, land uses, and education level). Therefore, management measures and policies should target their challenges according to these differences. For example, the highest population density within CMSES9 suggests that management and policies should target particular anthropogenic pressures, such as urban sprawl or an increase in resource consumption. In contrast, the challenge for CMSES11 is to manage the increasing population employed in the agricultural sector. In fact, the expansion of greenhouses and intensive agriculture in this CMSES has led to a loss of ecosystem services such as hydrological regulation, water purification, and aesthetic beauty (Garcia-Llorente et al., 2015; Requena-Mullor et al., 2018).

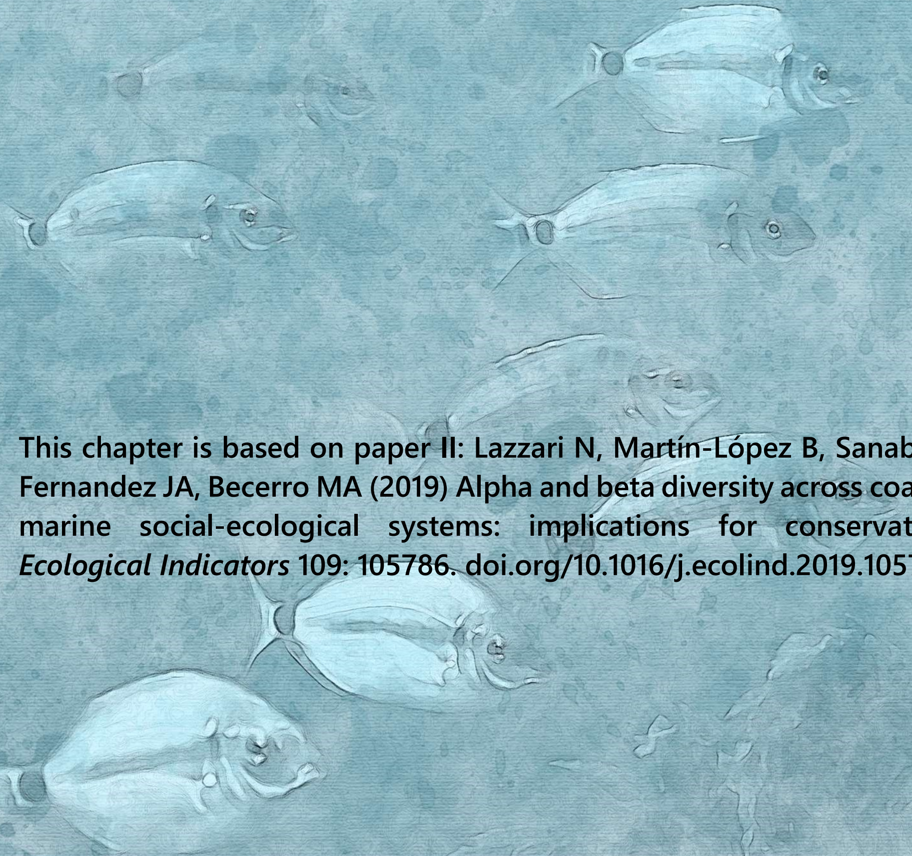
Almeria, with six CMSESs, was a perfect example of the high diversity of CMSESs within a single province: CMSES1, CMSES6, CMSES7, CMSES8, CMSES10, and CMSES11. The marine environmental characteristics divide the coastline of Almeria into a western region (CMSES1, CMSES10, and CMSES11) and an eastern region with warmer, salty, and unproductive water (CMSES6, CMSES7, and CMSES8). These characteristics were associated with the oceanographic variations of the Mediterranean Sea that show a gradual increase in SST and a gradual decrease in chlorophyll a with increasing distance from the Gibraltar Strait. In addition to marine environmental differences, socioeconomic differences highlight that specific management actions according to marine environmental and socioeconomic characteristics should be addressed. For instance, the high percentage of illiterate people in CMSES6, together with the low primary productivity of this area, suggests that management measures and policies should focus on environmental education oriented to promote sustainable fisheries. By comparison, the management challenge in CMSES7 and CMSES10 with a high percentage of terrestrial and marine protected areas is to increase and improve the surveillance of these protected areas to minimize poaching while promoting the development of new economic sectors with respect to nature, e.g., ecotourism.

The CMSESs identified in our study represent distinct associations between socioeconomic and marine environmental characteristics. Our results suggest new directions for coastal planning and management, which should focus on the specific characteristics and conservation challenges of each CMSES. As in other parts of the world, these conservation challenges range from reducing local human pressures, such as pollution derived from intensive agriculture (e.g., CMSES11) or urbanization of the coastline (e.g., CMSES9), to counteracting globally induced impacts such as climate change and overexploitation of fisheries (Anticamara et al., 2011; Broderick, 2015; de Andrés et al., 2017).

The Andalusian Regional Ministry of Environment and Territory has designed an integrated coastal zone management strategy that takes into account both the socioeconomic development and ecological fragility of the coastal system in the management of coastal and marine systems (Council of Europe, 2000). However, the differences between CMSESs were not considered. Although there is substantial progress in the integrated management of coastal marine areas in Andalusia, there are still important shortcomings (Barragán, 2003). First, the current management of the marine coastal areas in Andalusia seeks to address general problems, such as pollution, overfishing, biodiversity loss, reduction of economic possibilities, and loss of cultural and natural heritage, without appropriate consideration of CMSESs (Barragán et al., 2008). Second, the large number of institutions with coastal jurisdiction (e.g., Regional Ministry of Environment and Territory, the City Council, and the Spanish Ministry of Agriculture and Fisheries, Food and Environment) challenges coordination and jeopardizes an integrated management system that considers the distinctiveness of CMSESs (Barragán et al., 2008; Suárez de Vivero and Rodríguez Mateos, 2005). In this regard, our study provides a methodological framework that can facilitate the coordination between multiple institutions and integrate information from different sources.

The precise characterization of coastal regions in terms of socioeconomic and environmental variables can contribute to prioritizing the differential integrated management measures in each CMSES. Based on our results, distinctive management actions were identified according to the social-ecological characteristics of the CMSESs, such as environmental education programs, the control of agro-chemical consumption in intensive agriculture and the promotion of organic agriculture, or formal rules and norms that counteract current urban sprawl. In addition, the accurate spatial localization of CMSESs contributes to identifying the specific management actions required for each area and the stakeholders that should be involved. The methodological approach developed in this research effectively identified and characterized the social-ecological associations that occur in coastal marine systems. Our approach can therefore be a useful tool for designing more efficient management actions and policies that can be implemented at more relevant scales in marine coastal areas.

Chapter II: Alpha and beta diversity across coastal marine social-ecological systems: implications for conservation



This chapter is based on paper II: Lazzari N, Martín-López B, Sanabria-Fernandez JA, Becerro MA (2019) Alpha and beta diversity across coastal marine social-ecological systems: implications for conservation. *Ecological Indicators* 109: 105786. doi.org/10.1016/j.ecolind.2019.105786

Picture: School of Senegal seabream (*Diplodus bellottii*) in Alhucemas Islands (Spanish territories in the northern coast of Africa) by Natali Lazzari

4

Chapter II: Alpha and beta diversity across coastal marine social-ecological systems: implications for conservation

Abstract

Cumulative anthropogenic activities in coastal regions are a major threat to their marine biodiversity. The consideration of coastal marine areas as social-ecological systems (CMSESs) can be useful for marine biodiversity conservation. This integrative approach incorporates social information that can link anthropogenic activities to marine biodiversity, providing opportunities for improving conservation policies tailored to the specific reality of the CMSESs. Here, we assessed the beta and alpha diversity of the shallow littoral fish communities present in the Andalusian CMSESs and explored how they relate to socioeconomic and marine environmental variables. We used underwater visual surveys to estimate the fish abundance data needed to calculate the alpha and beta diversity of the fish species. We quantified the species and functional beta diversity using abundance-based data. We also quantified species richness index as indicators of species alpha diversity, and functional evenness as indicators of functional alpha diversity. We found that the association of marine environmental and socioeconomic variables with biodiversity varied with CMSES. Empirical inclusion of biodiversity in social-ecological systems research of marine and coastal areas can provide insights on human-nature dynamics. This can contribute to design more effective marine biodiversity conservation programs that consider both the socioeconomic and marine environmental characteristics of each CMSES.

4.1.Introduction

Oceans and seas have lost almost one percent of marine biodiversity per year in the last forty years (WWF, 2016). It seems an excessively high rate for a system that contributes so much to human quality of life through the provision of ecosystem services (Agardy et al., 2005; Liquete et al., 2013a) and that is essential for the social-ecological resilience (Beaumont et al., 2007; Martínez et al., 2007; Liquete et al., 2013b; Neumann et al., 2015). There is strong evidence that the cumulative and synergistic effects of multiple anthropogenic pressures including fisheries overexploitation, climate change, ocean acidification, pollution, and habitat destruction are jeopardizing the future of marine biodiversity (Halpern et al., 2008; Rocha et al., 2018). Not surprisingly, marine biodiversity is a conservation priority under numerous international agreements such as the Sustainable Development Goals (i.e., SDG 14) or the Convention on Biological Diversity Strategic Plan for Biodiversity (i.e., Aichi Target 11). Likewise, the scientific community is also addressing the conservation challenges of marine biodiversity by creating global research networks (Bennett, 2018) such as the Future Earth research cluster and knowledge-action-network on coasts (Future Earth Coasts, 2018; Future Earth Oceans, 2018) or the Taskforce on Ocean Governance of the Earth Systems Governance project (Earth System Governance, 2018). Along with these initiatives, UNESCO has announced that 2021–2030 will be the Decade of Ocean Science for Sustainable Development (UNESCO, 2018; Visbeck, 2018).

Scientifically, these initiatives stress the need for interdisciplinary research of marine biodiversity to ensure the sustainable use of the ocean. The social-ecological approach deepens in the study of human-nature dynamics, and it is particularly relevant for understanding how humans impact natural systems (Glaser et al., 2012). The social-ecological approach is well suited to provide insights about human-nature dynamics and, therefore, to contribute to reveal the management practices needed to preserve marine biodiversity (Christie et al., 2017; Bennett, 2018). Although the number of studies evaluating social-ecological interactions in coastal and marine systems has increased substantially in the last decade (e.g., Cinner et al., 2009; Álvarez-Romero et al., 2011; Ban et al., 2013), less than

15% of these studies included biodiversity aspects when analyzing the social-ecological dynamics of coastal and marine systems (Rissman and Gillon, 2017). Therefore, the need for biodiversity assessments in coastal and marine social-ecological systems (CMSESs) looms large.

The Mediterranean Sea is one of the most diverse and threatened marine biodiversity *hotspots* of the world (Myers et al., 2000; Coll et al., 2010, 2012). It hosts more than 600 fish species, which are highly threatened by direct and indirect anthropogenic impacts such as overfishing, marine pollution and fish species invasions (Reynolds et al., 2005; Coll et al., 2012). Recent studies on the western coast of the Mediterranean Sea evidence that coastal areas differ in socioeconomic and marine environmental characteristics (Lazzari et al., 2019). How these characteristics interact with biodiversity is yet unknown.

Our study aims to evidence the relationships between the alpha and beta biodiversity of littoral fish communities of the Andalusian coast, and the socioeconomic and marine environmental characteristics. Knowledge on such links may contribute to design management measures that effectively targeted the specific relationships between the environmental, socioeconomic, and biological characteristics of each CMSESs.

4.2. Study area

Our study covered part of the coastlines of Malaga, Granada, and Almeria provinces for an approximate total length of 300 km of the Andalusian region, in southern Spain (Fig. 4.1). The study area included six CMSESs. Each CMSES represents a homogenous area of varying size characterized by similar associations between socioeconomic and marine environmental variables (Lazzari et al., 2019). Despite their homogeneity, a single CMSES may occupy discontinuous geographic areas (Fig. 4.1).

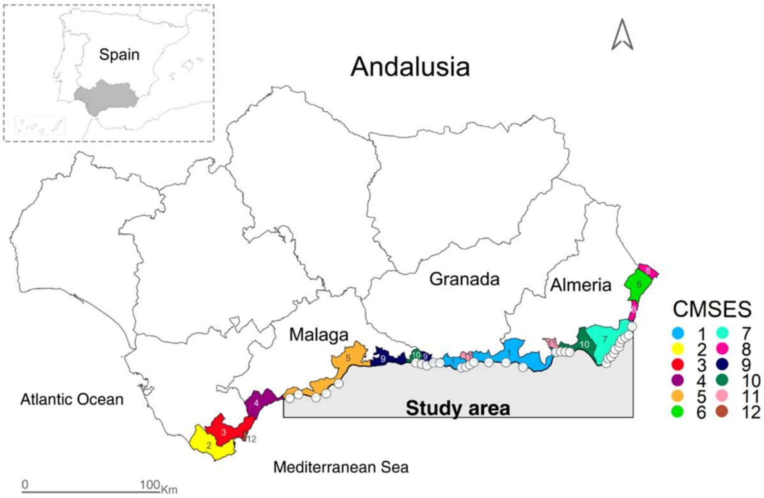
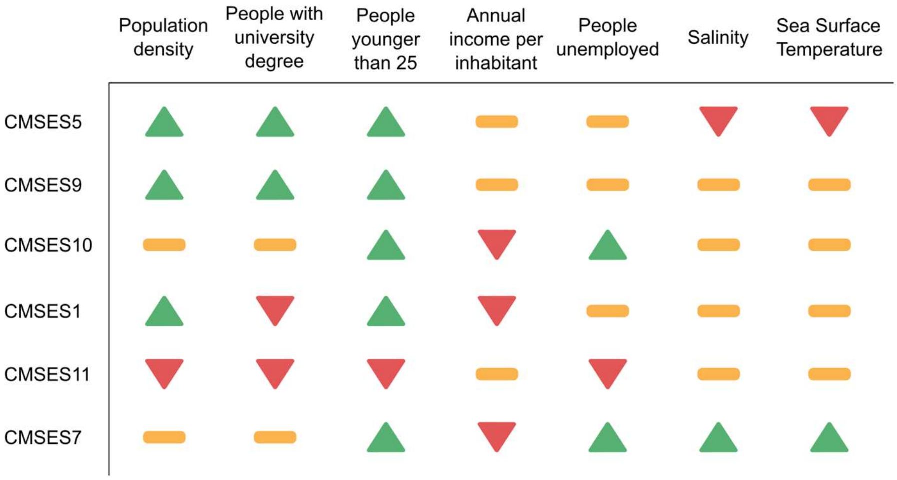


Figure 4.1. Map of the study area in the Mediterranean coast of Andalusia (grey box). The map shows the geographic location of the biological sampling points (white dots) and the coastal marine social-ecological systems (CMSES) to which they belong. We sampled six out of the 12 CMSESs in the region because they were the CMSESs with the highest percentage of hard substrate.

We sampled six CMSESs (i.e., CMSES5, CMSES9, CMSES10, CMSES1, CMSES11, and CMSES7, geographically ordered from west to east), which spread over several provinces (Fig. 4.1). In Malaga, we sampled CMSES5 and CMSES9. Both CMSESs share the same socioeconomic characteristics, presenting high population density and a high percentage of people with university-level education (Fig. 4.2). By contrast, the CMSES1 and CMSES11, which spread over the provinces of Granada and Almeria, have the lowest rate of people with university-level education. In Almeria, CMSES10 and CMSES7, together with CMSES1, have the lowest annual income per inhabitant (Fig. 4.2). Environmentally, CMSES5 and CMSES7 have the lowest and highest values of sea surface temperature and salinity, respectively, while the remaining CMSES9, CMSES10, CMSES1, and CMSES11 have intermediate values (Fig. 4.2). For more details, see Table S1 in Appendix for Chapter II and Lazzari et al. (2019).



	Population density	People with university degree	People younger than 25	Annual income per inhabitant	People unemployed	Salinity	Sea Surface Temperature
CMSES5	▲	▲	▲	▬	▬	▼	▼
CMSES9	▲	▲	▲	▬	▬	▬	▬
CMSES10	▬	▬	▲	▼	▲	▬	▬
CMSES1	▲	▼	▲	▼	▬	▬	▬
CMSES11	▼	▼	▼	▬	▼	▬	▬
CMSES7	▬	▬	▲	▼	▲	▲	▲

Figure 4.2. The seven socioeconomic and marine environmental variables contributing the most (>70%) to the characterization of CMSESs. Green up arrows, yellow lines, and red down arrows represent high, medium, and low values of each variable, respectively. To make the results comparative and descriptive, these classes were based on a relative classification of the variables, limited by their 33rd and 66th percentiles. CMSESs geographically ordered from west to east. For more details, see Table S1 in Appendix for Chapter II and Lazzari et al. (2019).

4.3.Data collection and analyses

4.3.1.Data sampling

We focused our study on the fish community inhabiting littoral rocky reefs of Andalusia. Fish are the most diverse vertebrate group, play an essential ecological role, and are highly impacted by anthropogenic activities such as overfishing (Reynolds et al., 2005). Following the standard Reef Life Survey (RLS) protocol, we collected fish abundance data from 53 sites in the six CMSESs of the Andalusian coast, during summer 2014-2016. We did a maximum of two transects per site, parallels to the coastline, and each site was distanced from others by at least 200 meters. We sampled 5 sites in CMSES5 and CMSES9, 6 sites in CMSES10, 11 sites in CMSES1, 8 sites in CMSES11 and 18 sites in CMSES7. RLS is a citizen science program that trains divers to collect biodiversity information using a standardized underwater visual census technique (Edgar and Stuart-Smith, 2014). Two RLS divers (NL and JASF) obtained 95% of the data used in this study. RLS divers count the abundance of each fish species sighted along a 50-m long, 5-m wide belt transect (total surface sampled = 250 m2), obtaining suitable data for the quantification of several biodiversity measures (Edgar and Stuart-Smith, 2014; Edgar et al., 2016, 2017). Full details of the standardized RLS survey procedures are available in an online methods manual (https://reeflifesurvey.com/wp-content/uploads/2015/07/NEW-Methods-Manual_150815.pdf).

4.3.2.Data analysis

Beta and alpha diversity

Species and functional beta diversity refer to the difference in species and functional traits between sites, respectively (Anderson et al., 2011). For fish species diversity, we generated a matrix of species by sites. To evaluate functional diversity of marine fish communities, we used 18 levels of five relevant functional traits (i.e. maximum length, trophic group, water column position, habitat complexity, and gregariousness; see Table 4.1), which were were obtained from FishBase (www.fishbase.org; Froese and Pauly, 2000) and the database used in Stuart-Smith et al. (2013). These traits provide information on key physiological, behavioral, and environmental aspects (Stuart-Smith et al., 2013; Mouillot et al., 2014). Then, we created a matrix of functional traits' levels by sites. The measurement of each species and each trait in a site was calculated as the average of its abundance for all transects in this site. Table S2 in Appendix for Chapter II shows how specific functional traits were assigned to each fish species. We used the log (x+1) transformed abundance data of species and functional traits, to calculate an abundance-based beta diversity indicator based on Bray-Curtis dissimilarity, which is less dependent on sample size than incidence-based beta diversity (Socolar et al., 2016). We used the beta.pair.abund function of the 'betapart' R package (Baselga, 2017) to calculate the abundance-based beta diversity indicator as the total pairwise dissimilarities of fish species and functional traits between sites (Baselga, 2017).

To estimate species alpha diversity, we used the indicator of species richness (i.e., the average of the total number of species of each transect in a site). We used the diversity function of the 'vegan' R package (Oksanen et al., 2019) to calculate the species richness. To quantify functional alpha diversity, we used functional evenness, which is defined as the uniform distribution of abundance in the functional trait space (Mason et al., 2005; Villéger et al., 2008). We selected this functional metric because it includes more than one functional trait and it is weighted by the relative abundances of species (Botta-Dukát, 2005; Villéger et al., 2008; Laliberté and Legendre, 2010). To calculate the functional evenness, we used the dbFD function of the 'FD' R package (Laliberté and Legendre, 2010).

Functional trait	Description	Levels
Maximum length	Species maximum length	Lm20 (less than 20 cm), lm20-40 (between 20-40 cm), lm40-60 (between 40-60 cm) and lm60 (more than 60 cm)
Trophic group	Species trophic niche	Browsing herbivore, benthic invertivore, planktivore, higher carnivore
Water column position	Species position in the water column	Benthic, demersal, site-attached pelagic, roaming pelagic
Habitat complexity	Habitat use	Typically associated with habitats characterized by low, medium, high complexity
Gregariousness	Intraspecific relationships	Solitary, paired, forming schools

Table 4.1. Functional traits of rocky reef fishes used to estimate functional diversity. Adapted from Stuart-Smith et al. (2013).

Socioeconomic and marine environmental variables

We used socioeconomic and marine environmental variables that were relevant in the characterization of CMSESs in Andalusia (Lazzari et al., 2019). We considered five socioeconomic aspects in our analysis: demography, economy, coastal land uses, sea use, and environmental protection. We obtained 24 socioeconomic variables, which were categorized in those five socioeconomic aspects. Variables were obtained from the Andalusian Multi-Territorial Information System, the Public Service State Employment and the Ministry of Agriculture, Fisheries and Food. Then, we performed a principal component analysis (PCA) of socioeconomic variables to reduce redundant information of each socioeconomic aspect, and to identify the new variables that characterize the differences between CMSESs (see Table S3 in Appendix for Chapter II). To name the new variables, we used those socioeconomic variables that had the highest square cosines and thus were the most relevant in explaining those PCA components with eigenvalue higher than one (Kaiser, 1960). The 24 original socioeconomic variables were reduced to ten variables distributed in the five socioeconomic aspects studied: demographic (population and illiteracy rate), economic (people employed in service sector, financial security and people employed in industry), land-use variables (urban, natural and agricultural land uses), sea-use variable (fisheries) and environmental protection (surface of protected area). See Table S3 in Apendix for Chapter II for additional information. In addition, we used six marine environmental variables that were found to characterize the CMSESs in Andalusia: primary productivity (mean chlorophyll a concentration), nutrients (nitrate and phosphate concentration), inorganic carbon (calcite concentration), salinity and sea surface temperature (mean sea surface temperature) (Lazzari et al., 2019).

Social-ecological relationships

To examine the relationships between beta diversity and socioeconomic and marine environmental variables, we performed distance-based redundancy analyses (db-RDA; Legendre and Anderson, 1999). This method is similar to redundancy analysis but based on a non-Euclidean distance measure. In this study, we used the Bray-Curtis dissimilarity to calculate the species and functional beta diversity. To perform the db-RDA analysis, we used the socioeconomic and marine environmental variables as explanatory variables and the beta diversity matrices of species and functional traits as response variables. We used the capscale functions of 'vegan' R package (Oksanen et al., 2019), to conduct the db-RDA analyses.

To inspect the relationships between alpha diversity and socioeconomic and marine environmental variables, we performed redundancy analyses (RDA; Legendre and Anderson, 1999). We used the socioeconomic and marine environmental variables as explanatory variables and the species and functional alpha diversity indices as response variables. To conduct the RDA analyses, we used the rda functions of 'vegan' R package (Oksanen et al., 2019), and the 'ggplot2' R package (Wickham, 2016) to perform the graphical representations (R Core Team, 2018).

4.4.Results

We found that species and functional beta diversity was related to different socioeconomic and marine environmental variables (F=1.490, p=0.001, Adjusted R2=0.131 and F=1.420, p=0.003, Adjusted R2=0.114, respectively). Species beta diversity of CMSES9 was associated with calcite concentration, while species beta diversity of CMSES7 and CMSES10 was associated with a higher surface of protected areas, a higher rate of illiteracy people, and a higher rate of people employed in industry (Fig. 4.3). The species beta diversity of CMSES5 was associated with those places where the rate of population employed in service sector was high. By contrast, the species beta diversity of CMSES11 was related to natural land uses (Fig. 4.3).

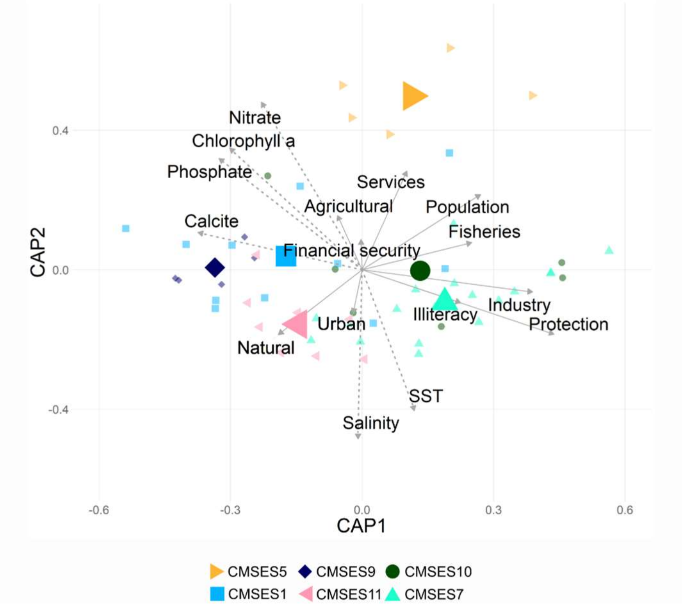


Figure 4.3. Distance based-redundancy analysis (db-RDA) biplot of weighted average scores for species beta diversity constrained by the socioeconomic (grey solid lines) and marine environmental variables (grey dashed lines). Population- population density and young people with a university degree;

Illiteracy- illiteracy rate; Fisheries-tons of fish landings and fishing vessels density; Financial security- annual income per inhabitant and employment rate; Services- people employed in service sector; Industry-people employed in industry; Urban-urban land uses; Natural-natural land uses; Agricultural-agricultural land uses; Protection-surface of protected area; Nitrate-nitrate concentration; Calcite-calcite concentration; Phosphate-phosphate concentration; Chlorophyll a-mean chlorophyll a concentration; SST-mean sea surface temperature.

Functional db-RDA showed that functional beta diversity of CMSES1, CMSES9, and CMSES11 was related with similar socioeconomic and marine environmental variables: high sea surface temperature, higher levels of salinity and calcite, and a higher surface of natural land uses (Fig. 4.4). Functional beta diversity of CMSES10 was associated with higher surfaces of protected areas and fisheries (Fig. 4.4). Functional beta diversity of CMSES5 was associated with a higher human population density, higher rates of people employed in industry and service sector and higher nitrate concentration. Finally, the functional beta diversity of CMSES7 did not show any preferential association with socioeconomic or environmental variables (Fig. 4.4).

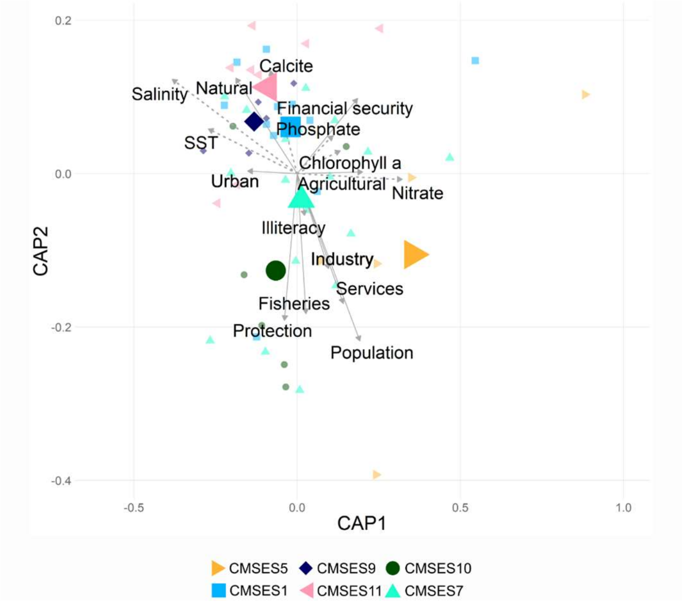


Figure 4.4. Distance based-redundancy analysis (db-RDA) biplot of weighted average scores for functional beta diversity constrained by the socioeconomic (grey solid lines) and marine environmental variables (grey dashed lines).

Population- population density and young people with a university degree; Illiteracy-illiteracy rate; Fisheries-tons of fish landings and fishing vessels density; Financial security-annual income per inhabitant and employment rate; Services-people employed in service sector; Industry-people employed in industry; Urban-urban land uses; Natural-natural land uses; Agricultural-agricultural land uses; Protection-surface of protected area; Nitrate-nitrate concentration; Calcite-calcite concentration; Phosphate-phosphate concentration; Chlorophyll a-mean chlorophyll a concentration; SST-mean sea surface temperature.

Regarding species and functional alpha diversity, we found that the species and functional alpha diversity indices were associated with different socioeconomic and marine environmental variables (F=1.666, p=0.033, Adjusted R2=0.170; Fig. 4.5). Species richness was positively related to natural land uses, higher protected surface, higher salinity, and sea surface temperature; whereas it was negatively associated with higher concentrations of nitrate, chlorophyll a, and phosphate (Fig. 4.5). Functional evenness was positively associated with higher financial security (i.e., high annual income per inhabitant and high employment rate) and people employed in service sector; whereas it was negatively associated with higher urban land uses and a higher rate of illiterate population (Fig. 4.5).

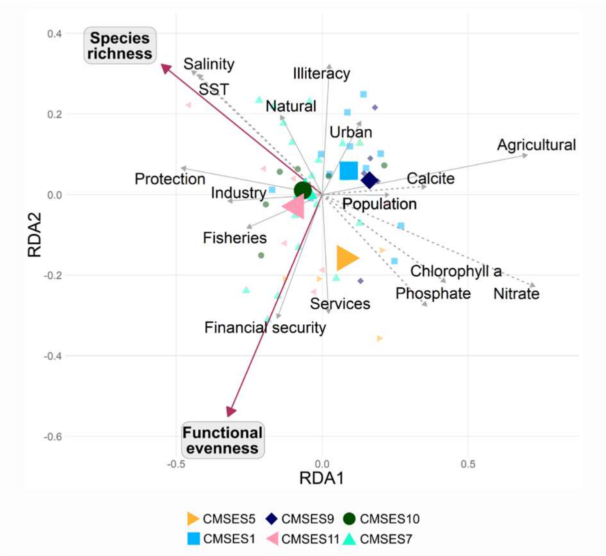


Figure 4.5. Redundancy analysis (RDA) biplot of weighted average scores for species and functional alpha diversity (pink arrows) constrained by the socioeconomic (grey solid lines) and marine environmental variables (grey

dashed lines). Population-population density and young people with a university degree; Illiteracy-illiteracy rate; Fisheries-tons of fish landings and fishing vessels density; Financial security-annual income per inhabitant and employment rate; Services-people employed in service sector; Industry-people employed in industry; Urban-urban land uses; Natural-natural land uses; Agricultural-agricultural land uses; Protection-surface of protected area; Nitrate-nitrate concentration; Calcite-calcite concentration; Phosphate-phosphate concentration; Chlorophyll a-mean chlorophyll a concentration; SST-mean sea surface temperature.

4.5.Discussion

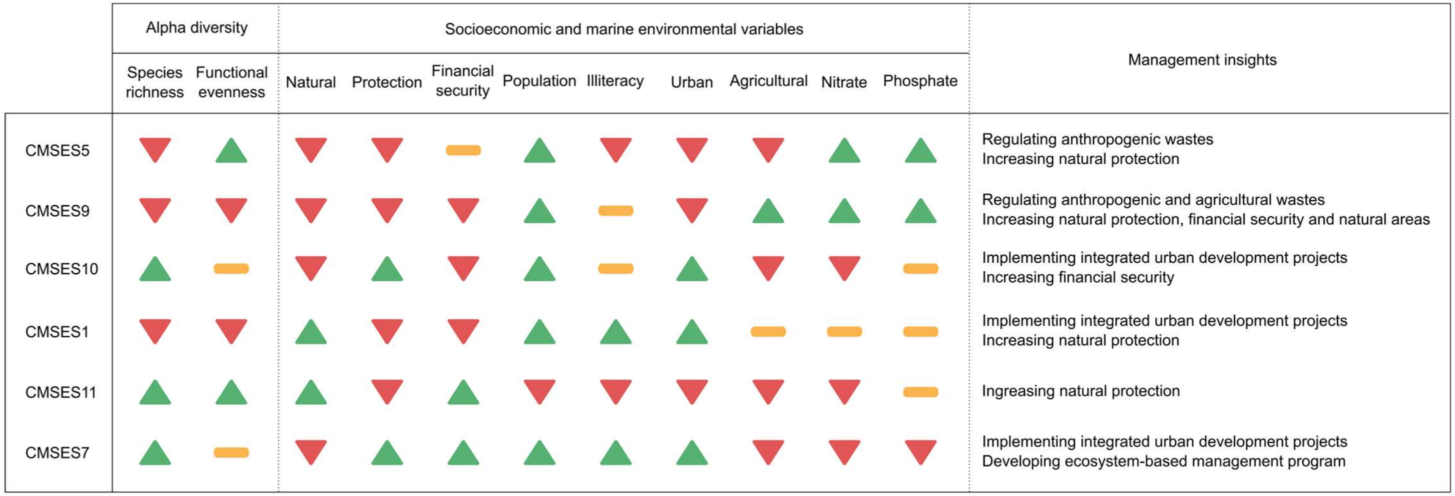
Our study showed how species community and functional structure are partially associated with socioeconomic and marine environmental variables that characterize CMSESs. This result supports the voices claiming that biodiversity assessments should be included in social-ecological systems (Rissman and Gillon, 2017; Mehring et al., 2017). Until now, the characterization of social-ecological systems has mainly considered environmental and socioeconomic factors (e.g. Castellarini et al., 2014; Martín-López et al., 2017; Lazzari et al., 2019), ecosystem services (Hamann et al., 2015; Sinare et al., 2016; Leenhardt et al., 2017) or land-uses (Alessa et al., 2009); but biodiversity has remained underexplored when characterizing social-ecological systems. Few studies have analyzed biodiversity patterns to characterize social-ecological systems. For example, Hanspach et al. (2016) found that species richness of butterflies, birds, and plants differ between social-ecological units in Transylvania (Romania). Based on these results, they suggest that different conservation measures should be implemented according to the biodiversity characteristics of each social-ecological unit. The lack of biodiversity assessments in social-ecological research of marine and coastal systems is even more remarkable than in terrestrial land systems (Rissman and Gillon, 2017). In marine systems, Leslie et al. (2015) and Mahboubi et al. (2015) used an expert-survey approach to assess biodiversity with a social-ecological approach; however, they did not empirically evaluate whether biodiversity varied among existing social-ecological systems. Therefore, to our best of knowledge, this study is the first one characterizing alpha and beta species and functional diversity in CMSESs.

This study advances social-ecological research on coastal and marine systems by assessing littoral fish biodiversity in six Andalusian CMSESs. We focused on both beta and alpha diversity of species community and functional traits because these metrics provide different information. While beta diversity informs about the different species/functional composition among sites, alpha diversity informs about the number of different species/functions in a site and how the species/functions are balanced in terms of abundance. Our study shows that the heterogeneous biological and functional beta and alpha diversity of CMSESs in Andalusia might be partially explained by the differences in socioeconomic and environmental variables characterizing the CMSESs, which might have implications for biodiversity conservation. For example, species and functional beta diversity of CMSES5 and CMSES9 were associated with different socioeconomic and environmental characteristics (Fig. 4.3 and Fig. 4.4). While beta diversity of CMSES5 was related to high concentrations of nitrates, a high human population density, and a high percentage of people working in the service sector; functional beta diversity of CMSES9 was related to high concentrations of calcite, and natural land uses. If the management of biodiversity in CMSES5 and CMSES9 focuses only on species richness, which is low in both CMSES, it might neglect the differences in the community functioning that might result from the different marine environmental and socioeconomic characteristics (Fig. 4.5). Therefore, one of the challenges of biodiversity conservation in coastal and marine systems is to design and develop management actions that are adapted to the different socioeconomic and environmental variables that characterize CMSESs (Fig. 4.6). For example, while the management of CMSES5 should consider the pollution derived from the nitrates used in agriculture and should foster increasing the surface of natural land uses; these management actions might be insufficient in CMSES9 (Fig. 4.6).

We also found that although some CMSESs such as CMSES1 and CMSES11, shared similar relationships between socioeconomic and environmental characteristics and functional beta diversity (Fig. 4.3 and Fig. 4.4), they presented different species and functional alpha diversity (Fig. 4.6). Functional beta diversity of both CMSESs was related to those areas representing natural land uses that also have higher values of calcite concentration, salinity, and phosphate concentration. However, species and functional alpha diversity presented opposite patterns as result of different socioeconomic and environmental conditions (Fig. 4.5; Fig. 4.6). The different environmental and socioeconomic conditions that relate to species and functional alpha diversity in CMSES1 and CMSES 11 might entail different management actions in these CMSESs. For example, to counteract the low species richness and functional evenness in CMSES1, management actions can promote integrated urban development to face the high population density and high urban land uses (Fig. 4.5; Fig. 4.6). Also, to preserve the high alpha diversity in CMSES11 while increasing in CMSES1, marine and terrestrial protection might be necessary in both CMSES.

We also found that those CMSESs characterized by a high percentage of protected areas, i.e., CMSES7 and CMSES10, host higher levels of species richness but medium functional evenness (Fig. 4.6). This result supported the findings of a recent study conducted in western Mediterranean that demonstrate that marine protected areas are more efficient in increasing fish biomass than in protecting species and functional diversity (Sanabria-Fernandez et al., 2019). Our study argues that management measures in western Mediterranean should focus on developing ecosystem-based management programs that consider both the human and ecological dimensions.

Given the proximity of the sampling sites and relatively uniform habitat characteristics of the Andalusian coastline, our results suggest that marine biodiversity is, at least in part, shaped by local social and environmental factors and that alpha and beta diversity matters in characterizing social-ecological systems. The biodiversity inclusion in the identification and characterization of marine social-ecological systems promotes the comprehensive integration of multiple socioeconomic, environmental, and biological dimensions in the analysis of CMSESs.



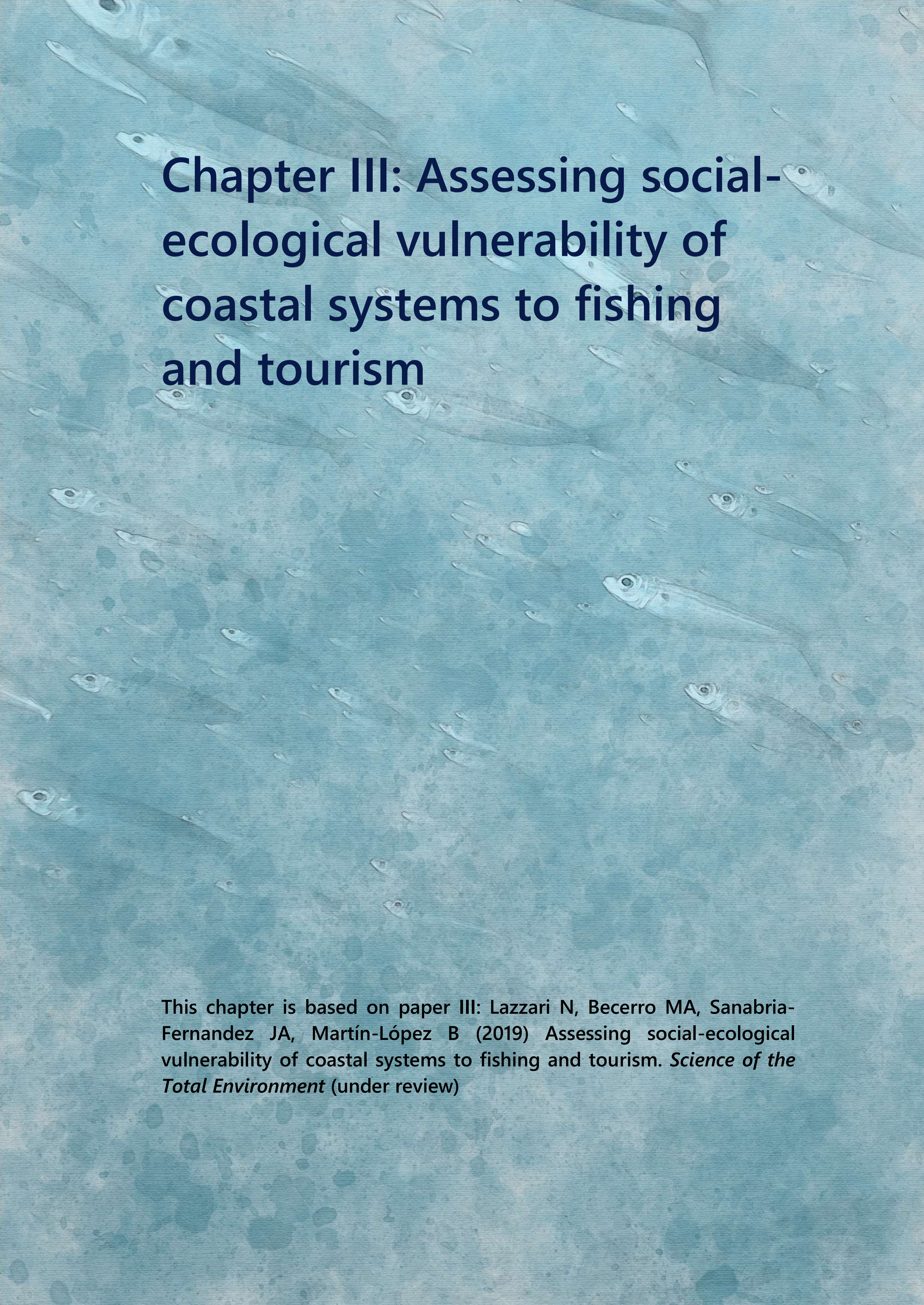
	Alpha diversity		Socioeconomic and marine environmental variables									Management insights
	Species richness	Functional evenness	Natural	Protection	Financial security	Population	Illiteracy	Urban	Agricultural	Nitrate	Phosphate	
CMSES5	▼	▲	▼	▼	▬	▲	▼	▼	▼	▲	▲	Regulating anthropogenic wastes Increasing natural protection
CMSES9	▼	▼	▼	▼	▼	▲	▬	▼	▲	▲	▲	Regulating anthropogenic and agricultural wastes Increasing natural protection, financial security and natural areas
CMSES10	▲	▬	▼	▲	▼	▲	▬	▲	▼	▼	▬	Implementing integrated urban development projects Increasing financial security
CMSES1	▼	▼	▲	▼	▼	▲	▲	▲	▬	▬	▬	Implementing integrated urban development projects Increasing natural protection
CMSES11	▲	▲	▲	▼	▲	▼	▼	▼	▼	▼	▬	Ingreasing natural protection
CMSES7	▲	▬	▼	▲	▲	▲	▲	▲	▼	▼	▼	Implementing integrated urban development projects Developing ecosystem-based management program

Figure 4.6. Summary of alpha diversity indices, socioeconomic and marine environmental variables related with species and functional alpha diversity and

management insights for biodiversity conservation. Green up arrows, yellow lines, and red down arrows represent high, medium, and low values of each variable, respectively. In order to make the results comparative and descriptive, these classes are based on a relative classification of the variables, limited by their 33rd and 66th percentiles. See Figure S1 in Appendix for Chapter II to visualize the alpha diversity variation among CMSESs.

4.6.Conclusions

This research showed that incorporating biodiversity metrics in social-ecological studies and considering social-ecological variables when assessing biodiversity, can be a promising strategy to design and develop more effective conservation and management actions in coastal and marine systems. Our study demonstrated that environmental and socioeconomic variables explain the fish community variation among CMSESs in alpha and beta diversity and their functional traits. By providing empirical information about the marine biodiversity of the Andalusian CMSESs, we hope to stimulate interdisciplinary social-ecological thinking in marine biodiversity conservation. In this sense, protection of marine biodiversity should consider not only the existing biodiversity in the Andalusian coastline but the socioeconomic and environmental variables underpinning such differences.



Chapter III: Assessing social-ecological vulnerability of coastal systems to fishing and tourism

This chapter is based on paper III: Lazzari N, Becerro MA, Sanabria-Fernandez JA, Martín-López B (2019) Assessing social-ecological vulnerability of coastal systems to fishing and tourism. *Science of the Total Environment* (under review)

Picture: School of Bogue *(Boops boops)* in Fuerteventura (Canary Islands, Spain) by Jose A. Sanabria-Fernandez

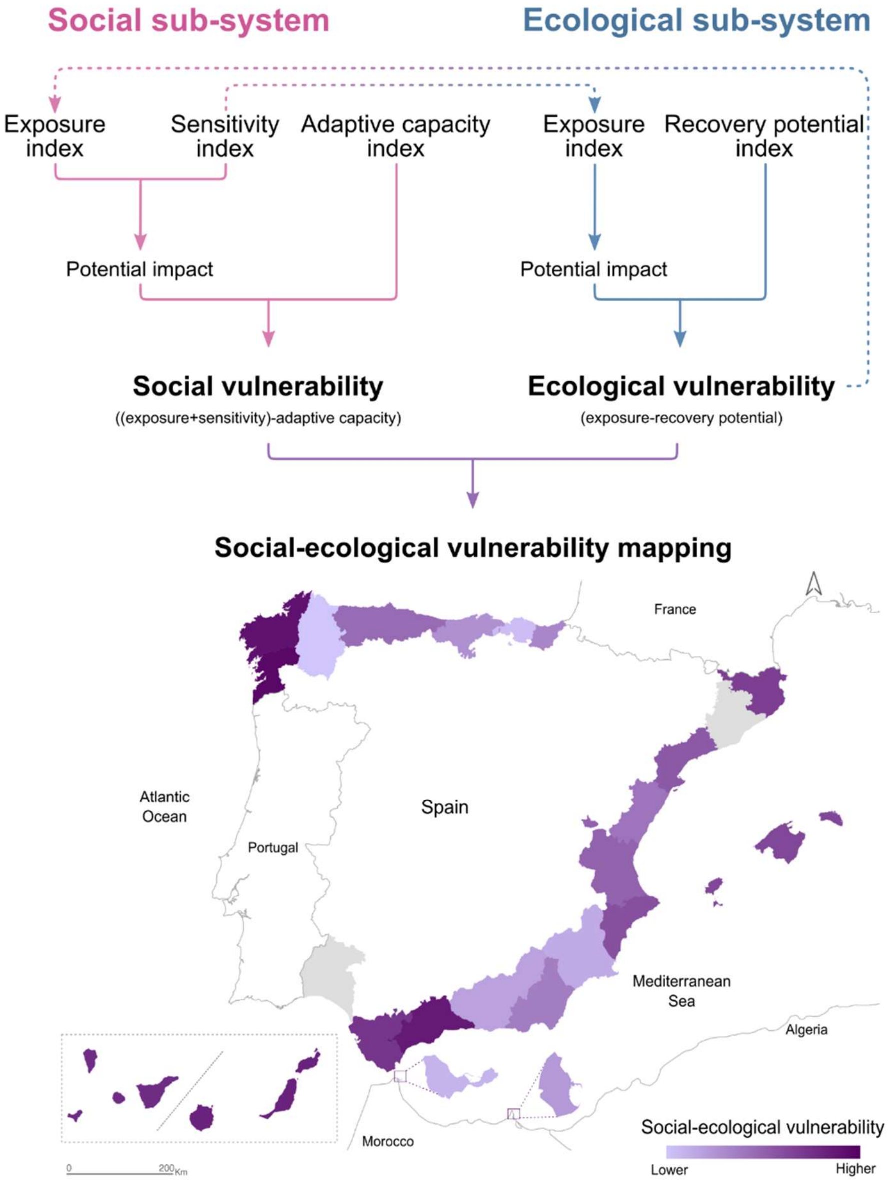
5

Chapter III: Assessing social-ecological vulnerability of coastal systems to fishing and tourism

Abstract

Detecting areas with high social-ecological vulnerability (SEV) is essential to better inform management interventions for building resilience in coastal systems. The SEV framework, developed by the Intergovernmental Panel on Climate Change, is a robust method to identify SEV of tropical coastal systems to climate change. Yet, the application of this framework to temperate regions and other drivers of change remains underexplored. This study operationalizes the SEV framework to assess the impact of fishing and tourism in temperate coastal systems. We spatially represented the SEV of coastal systems and identified the social and ecological vulnerability dimensions. Our results suggest that livelihood diversification and the protection of marine areas may be plausible strategies to build resilience in temperate coastal systems to fishing and tourism impacts. With this study, we hope to encourage the application of the SEV framework to other drivers of change for building more resilient coastal systems.

Graphical abstract



5.1.Introduction

Coastal marine systems (hereafter, coastal systems) are one of the most productive and biologically diverse systems of the planet (Agardy et al., 2005; Rogers et al., 2020). Coastal systems contribute to people's quality of life by supporting human livelihoods, regulating natural hazards, and providing cultural, spiritual, and aesthetics values (Agardy et al., 2005). Yet, as a result of the cumulative impact of anthropogenic activities, coastal systems are increasingly becoming socially and ecologically vulnerable (Agardy et al., 2005; Halpern et al., 2008).

Social-ecological vulnerability (SEV) is the magnitude at which systems are unable to cope with disturbances, which affects the systems' social and ecological sub-systems (Adger, 2006; Cinner et al., 2012). The SEV framework, formalized and promoted by the Intergovernmental Panel on Climate Change (IPCC), has proven to be a robust method for understanding the coastal system's responses to climate change (Marshall et al., 2009; Thiault et al., 2017). Its operationalization has been realized through assessments of SEV to climate change in tropical regions (e.g., Cinner et al., 2013; Siegel et al., 2019). As a result, the majority of management policies and programs aiming to reduce the vulnerability of coastal systems have mainly focused on mitigating climate change effects (Bennett et al., 2016). Yet, climate change is only one of the drivers of change causing coastal degradation (Agardy et al., 2005; Díaz et al., 2015). Other drivers of change, such as habitat alteration, overexploitation, and pollution affect coastal and marine biodiversity to a higher extent than climate change (Pereira et al., 2012; Luypaert et al., 2020; Rogers et al., 2020). Those multiple drivers of change stem from industries that rely on coastal systems such as fishing and tourism. Despite the critical role of assessing the capacity of coastal systems to cope with multiple disturbances plays when designing management actions, the operationalization of the SEV framework to drivers other than climate change remains a challenge (Thiault et al., 2017; Abelson, 2019).

Coastal systems nurture the fishing and tourism industries (Agardy et al., 2005; Bennett, 2019). Coastal artisanal fisheries, i.e., fisheries using vessels under 12 m in length (Quetglas et al., 2016; Villasante et al., 2016), represent 90% of the world's fishing fleet and fishers. Coastal systems are also important tourist destinations. About 50% of tourists spend time at the coastline and conducting recreational activities such as SCUBA diving, windsurfing, and recreational fishing (Orams, 1998; United Nations, 2017). In Spain, fishing and tourism highly contribute to the economic development of the country (Dirección General de Sostenibilidad de la Costa y del Mar, 2008; Losada et al., 2014). The high contribution of both activities to the economic development of Spain has been at the expense of preserving coastal and marine biodiversity. For example, the Spanish Millennium Ecosystem Assessment reported that coastal systems are the most degraded habitat in Spain (Spanish MEA, 2011). The Spanish Millennium Ecosystem Assessment also concluded that overexploitation of fisheries, urbanization, and climate change are the most important drivers of change in the Spanish coastal systems (Spanish MEA, 2011). Certain activities associated with fishing and tourism have turned coastal systems into highly vulnerable areas in Spain. Assessing the SEV of coastal systems may help identify the actual drivers of change and point to proper management actions. For example, identifying areas with low/medium vulnerability may suggest actions to mitigate the future impacts of fishing and tourism while restoration programs may be more adequate in highly vulnerable areas.

In this study, we aim to operationalize the SEV framework in temperate coastal systems where tourism and fishing activities are important drivers of change. First, we assessed the capacity of the coastal marine social-ecological system to cope with the impact caused by fishing and tourism in the Spanish coastal systems. Second, we mapped SEV *hotspots*, detecting areas of high social and ecological vulnerability. And third, we identified the key social and ecological dimensions underpinning vulnerability.

5.2.Study area

We applied the SEV framework to the Spanish coastal system, which encompasses almost 6,600 km-long distributed along five Marine Ecoregions of the World: i) South European Atlantic Shelf, ii) Azores Canaries Madeira, iii) Saharan Upwelling, iv) Alboran Sea, and v) Western Mediterranean (Fig. 5.1). The diverse biophysical characteristics of the

Spanish coastal system, such as the irregular underwater geography or upwelling areas, foster a wide variety of marine ecosystems with high biodiversity (Yepes and Medina, 2005; Coll et al., 2010). The Azores Canaries Madeira ecoregion is considered a transition zone where both sub-tropical and temperate marine species coexist (Brito et al., 2001; Tuya and Haroun, 2009; Freitas et al., 2019); the Western Mediterranean and the Alboran Sea ecoregions are located in the Mediterranean sea, which hosts one of the world's *hotspots* of marine biodiversity (Myers et al., 2000; Coll et al., 2010, 2012), and the South European Atlantic Shelf is one of the most productive areas of Spain (Ministerio de Medio Ambiente y Medio Rural y Marino, 2008).

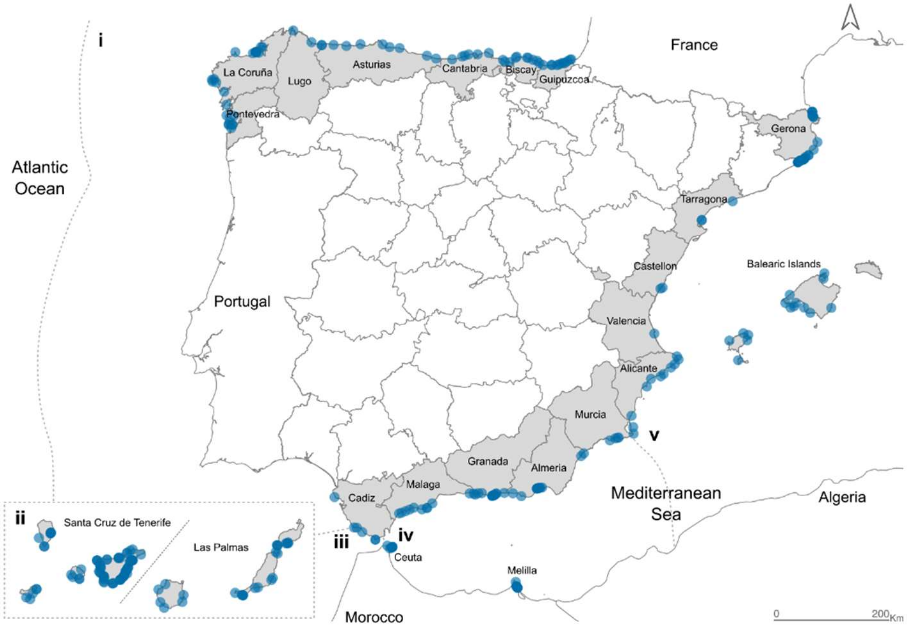


Figure 5.1. Map of the study area showing the geographical location of the Spanish coastal provinces sampled (grey polygons), and biological sampling sites (blue circles). Dashed lines represent the limits of marine ecoregions: (i) South European Atlantic Shelf, (ii) Azores Canaries Madeira, (iii) Saharan Upwelling, (iv) Alboran Sea, and (v) Western Mediterranean.

In terms of the socio-economic characteristics, coastal provinces represent 31% of the total surface of Spain and host 60% of the Spanish population. The coastal system hosts a wide variety of human activities such as fishing and tourism. The Spanish economy depends largely on these two activities. Fishing in Spain provides more than 30,000 direct jobs and yields a landing over 900,000 tons of fish per year, being the European country with the highest fish production (Confederación Española de Pesca, 2019). Tourism in the Spanish coastal systems provides 2.5 millions of direct jobs and, approximately, 90% of nights spent in tourism facilities in Spain occur in coastal areas (Eurostat, 2019).

5.3.Methods

5.3.1.Methodological framework

To evaluate the SEV (social-ecological vulnerability) to fishing and tourism in coastal systems we adapted the vulnerability framework originally designed for climate change assessments (Marshall et al., 2009; Fig. 5.2). We defined the vulnerability of a coastal system as a combination of the exposure and sensitivity to a potential impact resulting in social and ecological changes and the adaptive capacity of the system to cope with such impact (Adger, 2006; Marshall et al., 2009; Fig. 5.2). Exposure refers to the extent to which a region experiences social or ecological stress (Cinner et al., 2013). In the context of our study, we defined social exposure as the magnitude by which fishing and tourism areas are potentially exposed to ecological vulnerability (Fig. 5.2). We defined Ecological exposure as the magnitude of fishing and tourism pressures to which the ecological dimension is exposed (Fig. 5.2). For instance, in rocky reef ecosystems, exposure to overfishing may lead to biodiversity loss and changes in the trophic chain (Maureaud et al., 2017), whereas the exposure to a high density of SCUBA divers may be a driver of habitat destruction (Giglio et al., 2020).

We defined sensitivity as the set of conditions and characteristics that mediate the propensity of a particular region to be influenced by fishing and tourism pressures (adapted from Bousquet et al., 2015). Therefore, social sensitivity in this study refers to the degree by which people depend on fishing and tourism (Fig. 5.2), whereas ecological sensitivity is the degree to which an ecological system is affected by fishing and tourism pressures (Marshall et al., 2009). For example, social systems are more sensitive to ecological changes if they are highly dependent on a vulnerable natural resource (Cinner et al., 2013).

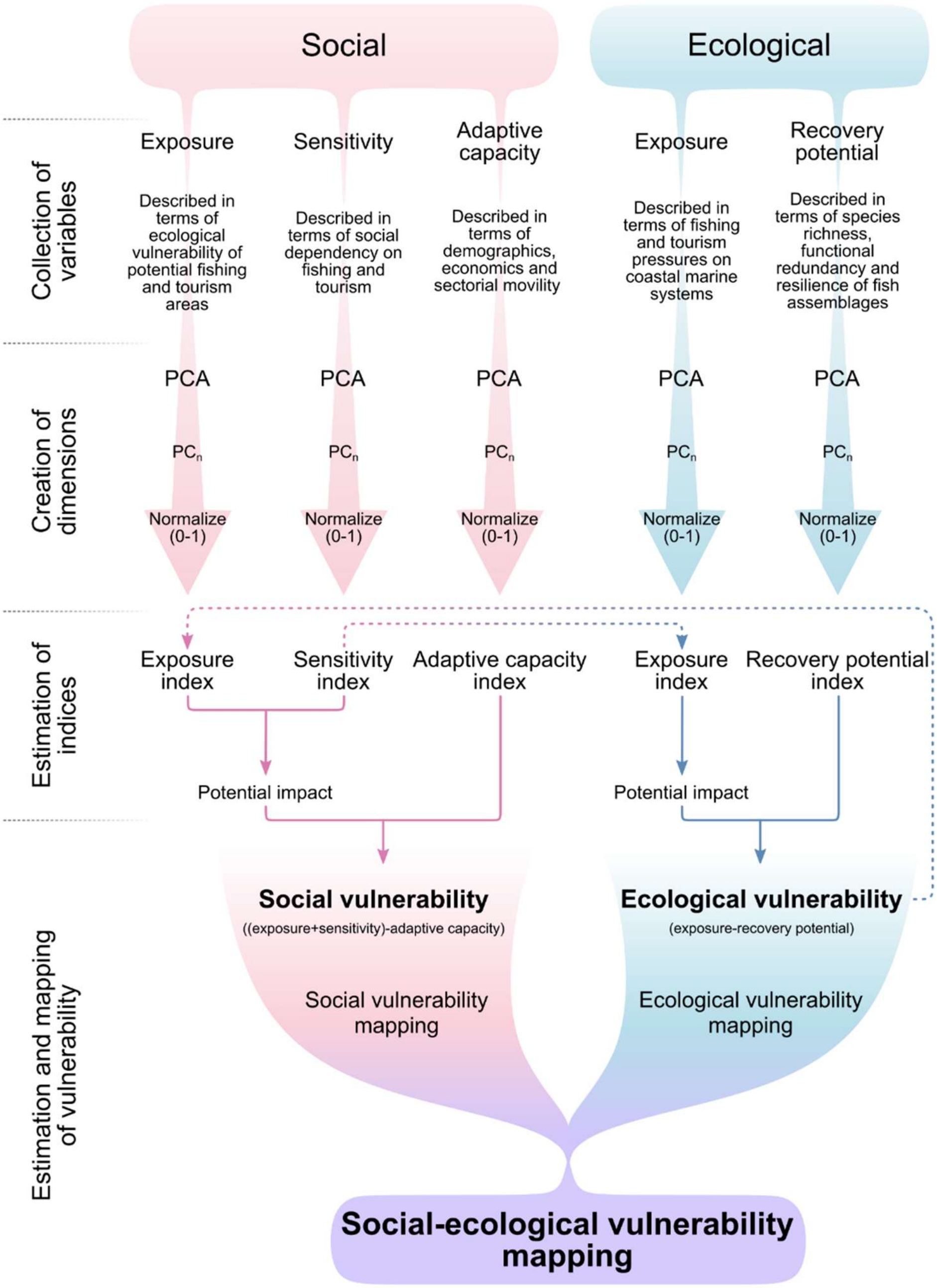


Figure 5.2. Methodological approach used to operationalize the social-ecological vulnerability framework in the Spanish coastal system.

Finally, adaptive capacity captures the ability to respond and to address social and ecological changes by mitigating, coping with, and recovering from the potential impact caused by a particular pressure (Thiault et al., 2019a). Here, we defined the social adaptive capacity as the set of demographical, economic, and mobility characteristics that enhance people's ability to mitigate, cope, and recover from the potential impacts caused by fishing and tourism (Fig. 5.2). For example, high social adaptive capacity may promote people’s ability to adapt to changes in fishing and tourism or to take advantage of the opportunities created by these changes (Cinner et al., 2013). Since the ecological adaptive capacity also depends on inherent characteristics of the ecological community, in this study, we integrated ecological sensitivity and ecological adaptive capacity under the umbrella of the so-called recovery potential (Cinner et al., 2013; Thiault et al., 2017). Therefore, recovery potential refers to those characteristics of the ecological community that mediate the capacity of the ecosystem to respond to fishing and tourism pressures (Fig. 5.2).

5.3.2.Methodological approach

Data collection

To assess the SEV to fishing and tourism in Spanish coastal systems, we collected both relevant ecological and socio-economic information (Table S1 in Appendix for Chapter III). To calculate the recovery potential, we collected data on the fish community inhabiting littoral rocky reefs of the Spanish coastline (Table S1 in Appendix for Chapter III). We focused our study on the fish community because fish represent an important tourist attraction, are a major protein source for humans, and are highly impacted by human activities such as coastal development or overfishing (Agardy et al., 2005; Reynolds et al., 2005; Halpern et al., 2008). We collected fish abundance data from 291 sampling sites scattered along the Spanish coastline following the standard Reef Life Survey (RLS) protocol (Edgar and Stuart-smith, 2014). Each sampling site, distanced from others by at least 200 m, represented one or more transects parallels to the coastline (average of 1.8 transects per site). Using the RLS underwater visual census, we estimated the abundance of each fish species sighted along a 50 m long, 5 m wide belt transect (total surface sampled=250 m2) (Edgar and Stuart-smith, 2014; Edgar et al., 2016, 2017). For more details of the standardized RLS survey procedures check the online methods manual (https://reeflifesurvey.com/wp-content/uploads/2015/07/NEW-Methods-Manual_150815.pdf).

We used the biological information collected through RLS to build three variables that were used to calculate recovery potential: i.e. species richness, functional redundancy, and resilience to fishing (Table S1 in Appendix for Chapter III). Species richness was calculated as the average of the total number of fish species per sampling site. To estimate species richness, we used the diversity function of the ‘vegan’ R package (Oksanen et al., 2019). To estimate functional redundancy, we used five relevant functional traits of fish that provide information on key physiological, behavioral, and environmental aspects (i.e. maximum length, trophic group, water column position, habitat complexity, and gregariousness) (Stuart-Smith et al., 2013; Mouillot et al., 2014). We obtained traits information from FishBase (www.fishbase.org; Froese and Pauly, 2000) and Stuart-Smith et al. (2013). Then, we used the dbFD function of the ‘FD’ R package (Laliberté and Legendre, 2010) to quantify the Rao's quadratic entropy (RaoQ) used as a measure of functional redundancy (Botta-Dukát, 2005). Finally, we estimated the resilience to fishing, such as the ability of fish species to recover from the fishing impact. We defined resilience to fishing as the opposite of the intrinsic vulnerability index developed by Cheung et al. (2005). For each fish species, we estimated the resilience to fishing weighted by their abundance, then we used the community-weighted mean as the resilience to fishing variable (Thiault et al., 2017; Table S1 in Appendix for Chapter III).

We focused our study area on those coastal provinces where large rocky bottom habitats are present. These areas span all over the Spanish littoral, including the mainland, the main islands, and small territories of the Mediterranean coast of North Africa (“Santa Cruz de Tenerife”, “Las Palmas”, Balearic Islands, “Ceuta”, “Melilla”, “Gerona”, “Tarragona”, Castellon, “Valencia”, “Alicante”, “Murcia”, Almeria, “Granada”, Malaga, Cadiz, “Pontevedra”, “La Coruña”, “Lugo”, “Asturias”, “Cantabria”, Biscay, and

Guipuzcoa, Fig. 5.1). To calculate the social indices of sensitivity and adaptive capacity, we collected socio-economic information on the fishing and tourism industries. The index of social sensitivity included information from five different variables (Table S1 in Appendix for Chapter III): fish consumption (percentage of annual fish consumption), level of employment in fishing and hotel industries (percentage of contracts on fishing and hotel industries), tourist accommodation (number of hotel rooms), and tourist room profit (profit in euros per tourist room by day). The index of social adaptive capacity included information from five variables (Table S1 in Appendix for Chapter III): literacy (inhabitants with elementary school or a higher education level), multidimensional wealth (based on the income distribution and consumption patterns), unidimensional wealth (based on the family capacity to live between consecutive wages without difficulties), and mobility in the primary (number of contracts in agriculture and fishing industries that involve interprovincial displacement) and tertiary (number of contracts in a service industry that involves interprovincial displacement) sectors. Besides, we also used socio-economic information to calculate ecological exposure. Ecological exposure included eight variables (Table S1 in Appendix for Chapter III): fishing vessels (number of artisanal fishing vessels per km of coastline), fishing vessel gross tonnage (volume capacity of all artisanal fishing vessels per km of coastline), fish landings (tons per km of coastline of littoral fish extracted), recreational fishing and underwater activities licenses (number of fishing licenses and underwater activities licenses per km of coastline), recreational vessels registration (number of new recreational vessels registered per km of coastline), dive centers (number of dive centers per km of coastline) and tourism (number of tourists per km2). All socio-economic data came from several national and international public databases: Spanish Statistical Office, Public Service State Employment, Ministry of Agriculture, Fisheries and Food, The Food and Agriculture Organization, Superior Sports Council, National Association of Nautical Companies (Table S1 in Appendix for Chapter III).

Finally, we used two variables to calculate social exposure: the fishing industry exposure, understood as the average ecological vulnerability of the potential fishing area, and the tourism industry exposure, understood as the average ecological vulnerability of the potential tourism area. Because artisanal fisheries in Spain operate with artisanal vessels in an area close to the port of departure, we estimated the fishing industry exposure as the average ecological vulnerability within a buffer area of 12 nautical miles from each Spanish port with artisanal fisheries (Soltanpour et al., 2017). The distance traveled by tourists varies with location but, in general, the number of visitors to recreation sites decreases with distance (Alves et al., 2017). Tourists' mobility in southern Spain ranges between 20 and 300 km (Martín-López et al., 2009), so we assumed an average displacement of 100 km. To estimate the tourism industry exposure, we measured the average ecological vulnerability within a buffer area of 100 km from the geographical center of each coastal municipality.

From variables to vulnerability indices and maps

To calculate the indices of social and ecological exposure, sensitivity, adaptive capacity, and recovery potential for both fishing and tourism pressures, we separately conducted five principal component analysis (PCA, one for each index) to unveil the dominant relationships between variables that define different dimensions (see Section *Data collection*.; Fig. 5.2). We used varimax rotation in some indices to facilitate the interpretation. We assumed that the principal components (PCs) obtained through the PCAs represent different dimensions of social and ecological exposure, sensitivity, adaptive capacity, and recovery potential.

Before computing the PCAs, all variables were log-transformed (x+1) and scaled to avoid heteroscedasticity. To test the suitability of the data for PCA, we used Kaiser-Meyer-Olkin (KMO) and Bartlett's tests. KMO is a measure of sampling adequacy that indicates the proportion of common variance. Bartlett’s test indicates whether the correlation matrix is an identity matrix or not, which indicates whether variables are unrelated. Values of KMO higher than 0.5 and significant Bartlett’s test ($p < 0.05$) indicate that the data might be suitable for PCA.

In each of the five PCA, we retained those PCs with an eigenvalue larger than 1 (Kaiser, 1960) to identify the different coherent dimensions that explain social and ecological exposure, sensitivity, adaptive capacity, and recovery potential. The factor loadings of the original variables on the retained PCs informed about the different dimensions underpinning the five vulnerability indices. Finally, the dimensions were combined into single and un-weighted indices of social and ecological exposure, sensitivity, adaptive capacity, and recovery potential (Fig. 5.2).

To estimate the social, ecological, and social-ecological vulnerability we applied an additive approach among indices, which assumed that all the indices had equal importance. As presented in Figure 4.2, social vulnerability was calculated as (exposure + sensitivity) - adaptive capacity; ecological vulnerability was estimated as exposure - recovery potential; and SEV was calculated as social vulnerability + ecological vulnerability (Hughes et al., 2012; Thiault et al., 2017).

Finally, to visualize spatial differences in social, ecological and social-ecological vulnerability to fishing and tourism in Spain, we mapped the social, ecological, and social-ecological vulnerability of the Spanish coastal provinces using the Free and Open Source Geographic Information System QGIS (QGIS Development Team, 2019). Besides, we created scatter-plots to graphically represent the recovery potential and the social adaptive capacity against the pressure from tourism and fishing activities. We also presented in a scatter-plot the existing SEV to tourism and fishing. Then, we conducted a PCA to unveil the multivariate relationships among the ecological and social vulnerability dimensions and the coastal provinces in Spain. We used R software (R Core Team, 2018) to conduct all the statistical analyses and graphical representations.

5.4.Results

5.4.1.Creating the dimensions of vulnerability indices

We found eight social-ecological dimensions for social and ecological exposure, sensitivity, adaptive capacity, and recovery potential for both fishing and tourism: exposure of the social system to ecological vulnerability, dependency on fishing, dependency on tourism, adaptive capacity of the social system, fishing pressure, pressure from local recreational activities, pressure from non-local recreational activities, and recovery potential of the fish community (Fig. 5.3). First, social exposure was represented by the first

PC (98% of variance), which indicated the exposure of the social system to ecological vulnerability. PC1-Exposure of the social system to ecological vulnerability presented in its positive loads the variables fishing industry and tourism industry exposure (Table S2 in Appendix for Chapter III). Second, for social sensitivity, we retained the first two rotated PCs, which explained 87% of the variance: PC1 (48% of variance) and PC2 (39% of variance) (Table S2 in Appendix for Chapter III). PC1-Dependency on tourism included tourist accommodation, tourist room profit, and employment in the hotel industry. PC2-Dependency on fishing included fish consumption and employment in the fishing industry in its positive loads (Table S2 in Appendix for Chapter III). Third, we retained the first PC (68% of variance) to represent social adaptive capacity. PC1-Adaptive capacity of the social system included all the variables considered for social adaptive capacity: multidimensional wealth, unidimensional wealth, literacy, mobility in the primary sector, and mobility in the tertiary sector (Table S2 in Appendix for Chapter III).

Fourth, for ecological exposure, we retained the first three rotated PCs that explain 79% of the variance (Table S2 in Appendix for Chapter III). PC1-Fishing pressure (31% of variance) included the variables of fishing vessels, fishing vessel gross tonnage, and fish landings. PC2-Pressure from local recreational activities (31% of variance) included licenses for recreational fishing, licenses for underwater activities, and recreational boat registration. PC3-Pressure from non-local recreational activities (18% of variance) included the dive centers and tourism (Table S2 in Appendix for Chapter III). Finally, we retained the first PC-Recovery potential of the fish community (54% of variance) that included species richness, functional redundancy, and resilience to fishing (Table S2 in Appendix for Chapter III).

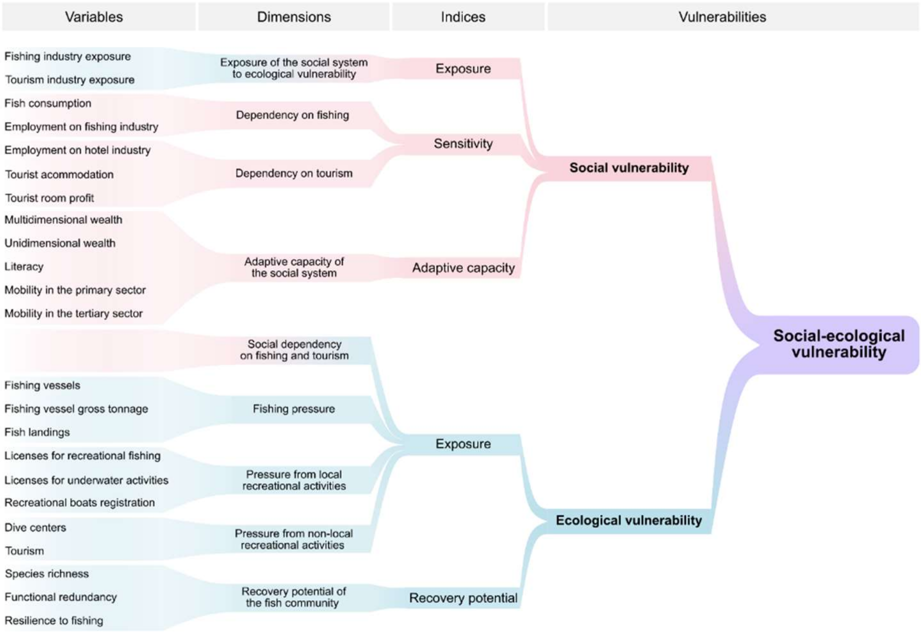


Figure 5.3. Relation of the terms used to appoint the variables, dimensions, indices, and vulnerabilities.

5.4.2.Social vulnerability

For social vulnerability, we calculate three indices: social exposure, social sensitivity, and social adaptive capacity (Fig. 5.3). Social exposure and adaptive capacity were estimated through the dimensions of exposure of the social system to ecological vulnerability and adaptive capacity of the social system, respectively. We calculated social sensitivity through the dimensions of dependency on fishing and dependency on tourism.

The highest and the lowest social vulnerability was found in the Atlantic region, in “Pontevedra” and Biscay, respectively (Fig. 5.4a). Nearly half of the Atlantic provinces presented high social vulnerability, whereas 33% of the Atlantic provinces presented low social vulnerability. The Mediterranean region presented an even distribution of high and low social vulnerability, with 23% of the region belonging to both cases. In the Mediterranean region, Malaga and Cadiz had the highest ecological vulnerability, while “Ceuta” and “Melilla” had the lowest.

Balearic Islands, “Santa Cruz de Tenerife”, and “Las Palmas” presented a higher dependency on tourism (Fig. 5.4b), whereas the provinces of “Pontevedra” and “La Coruña” had the highest dependency on fishing (Fig. 5.4c).

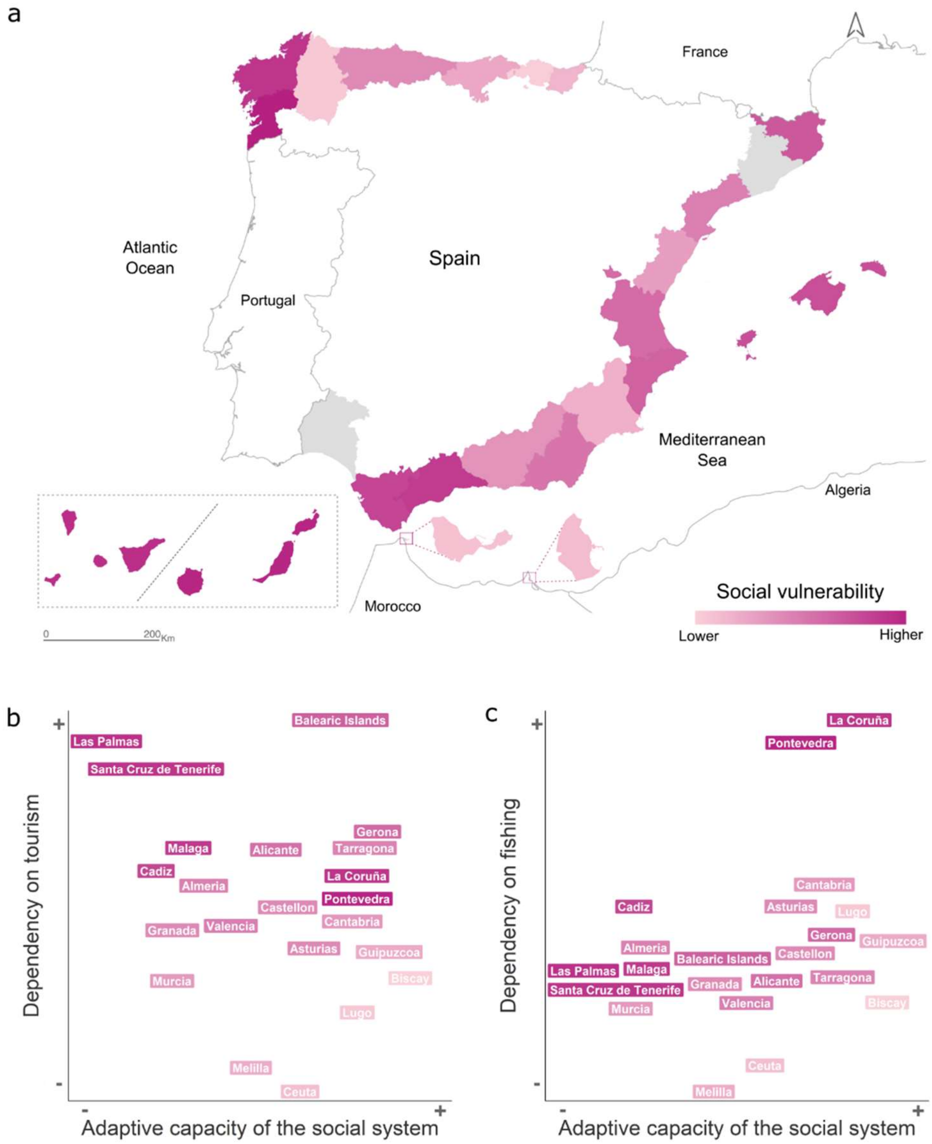


Figure 5.4. Social vulnerability of Spanish coastal provinces to dependencies on tourism and fishing. (a) Map of spatial variation of social vulnerability. Breakdown of social vulnerability according to the (b) dependency on tourism and (c) dependency on fishing.

5.4.3.Ecological vulnerability

For ecological vulnerability, we calculated two indices: ecological exposure and recovery potential (Fig. 5.3). Ecological exposure included three ecological dimensions (fishing pressure, pressure from local recreational activities, and pressure from non-local recreational activities) and two social dimensions (dependency on fishing and dependency on tourism) (Fig. 5.3). We estimated recovery potential with the dimension of the recovery potential of the fish community (Fig. 5.3).

We found that the Atlantic region presented 22% of its coastal system with high ecological vulnerability and 33% with low ecological vulnerability (Fig. 5.5a). The highest ecological vulnerability in the Atlantic region lies in "Pontevedra" and "La Coruña", while the lowest lies in "Lugo" and Biscay. The Mediterranean region presented 15% and 32% of its coastal system with high and low ecological vulnerability, respectively (Fig. 5.5a). In the Mediterranean region, we found that "Gerona" had the highest ecological vulnerability, followed by "Alicante", Malaga, and "Tarragona".

Whereas the Mediterranean provinces of "Gerona", "Alicante", "Melilla", Balearic Islands, and Malaga withstood higher pressure from recreational activities (Fig. 5.5b), the Atlantic provinces of "Pontevedra" and "La Coruña" withstood the highest pressure from fishing activities (Fig. 5.5c).

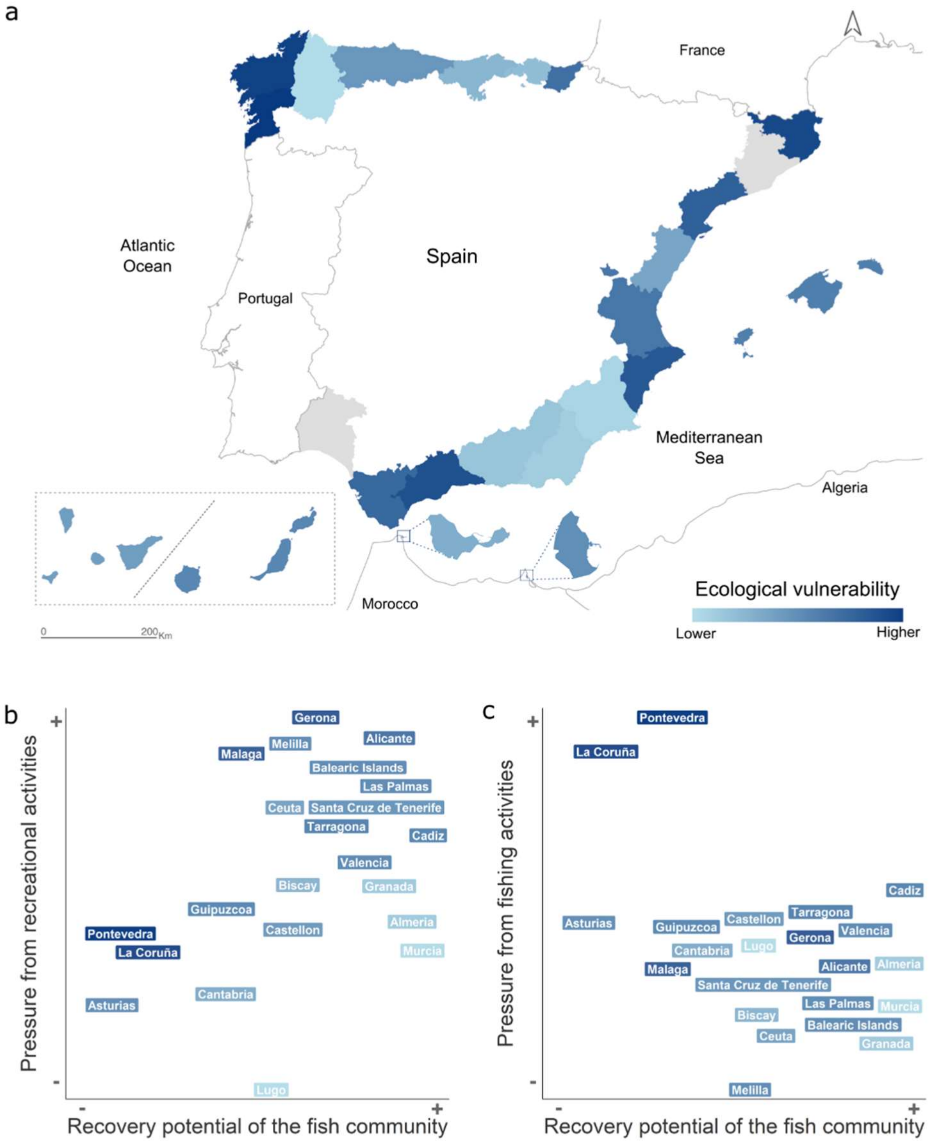


Figure 5.5. Ecological vulnerability of Spanish coastal provinces to tourism and fishing pressures. (a) Map of spatial variation of ecological vulnerability. Breakdown of ecological vulnerability according to (b) pressure from recreational activities and (c) pressure from fishing activities. Both indicators were represented against the recovery potential of fish community. The color gradient from light blue to dark blue shows the gradient from lower to higher ecological vulnerability.

5.4.4.Social-ecological vulnerability (SEV)

Overall, we found that 44% of the Atlantic Region and 23% of the Mediterranean Region had high levels of SEV. We found that the coastal system with the highest SEV was located in "Pontevedra" and "La Coruña", in the Atlantic Region, followed by Malaga in the Mediterranean Region (Fig. 5.6a). While the high SEV of "Las Palmas", "Santa Cruz de Tenerife", and "Gerona" was related to their vulnerability to tourism, the high SEV of "Pontevedra" and "La Coruña" was associated with their vulnerability to fishing. Malaga and Cadiz presented intermediate values of both social-ecological vulnerabilities to tourism and fishing (Fig. 5.6b).

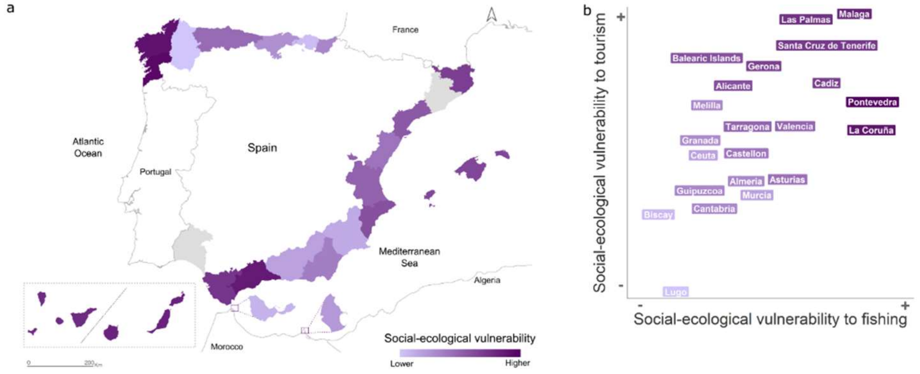


Figure 5.6. Social-ecological vulnerability of Spanish coastal provinces to tourism and fishing. (a) Map of spatial variation of social-ecological vulnerability. (b) Scatter plot representing the social-ecological vulnerability to tourism against social-ecological vulnerability to fishing. The color gradient from light violet to dark violet shows the gradient from lower to higher social-ecological vulnerability.

The first two axes of the PCA explained 58.6% of the variation among the social and ecological vulnerability dimensions across provinces (Fig. 5.7). Positive scores of PC1 (33.8% of variance) represented those areas with higher pressure from fishing, dependency on fishing, exposure of the social system to ecological vulnerability (i.e., "Pontevedra" and "La Coruña"), and with a higher adaptive capacity of the social system ("Asturias" and Guipuzcoa). Conversely, negative scores of PC1 represented those provinces with higher pressure from non-local recreational activities (Balearic Islands, "Santa Cruz de Tenerife", and "Las Palmas") and recovery potential of the fish community. PC2 (24.8% of variance) represented those areas with a higher dependency on tourism (Balearic Islands, "Santa Cruz de Tenerife", and "Las Palmas"). Negative scores of PC2 represented those provinces with higher pressure from local recreational activities (Biscay and "Lugo") (Fig. 5.7). The provinces with high SEV were differently associated with tourism and fishing. For example, "Pontevedra" and "La Coruña" were related to higher dependency on fishing, fishing pressure, and exposure of the social system to ecological vulnerability. "Las Palmas" and "Santa Cruz de Tenerife" were related to higher dependency on tourism and pressure from non-local recreational activities (Fig. 5.7).

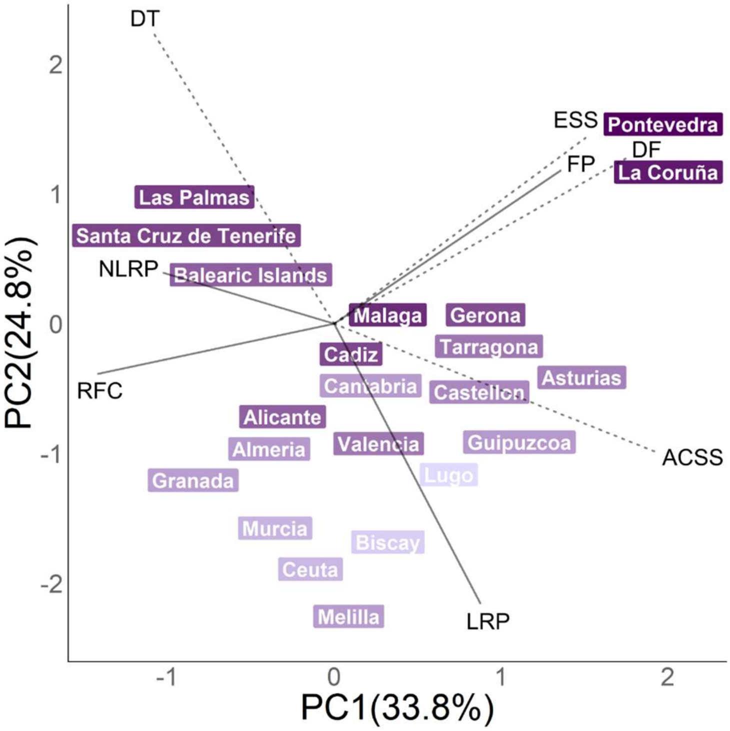


Figure 5.7. Principal component analysis of the four social (grey dashed lines) and four ecological (grey solid lines) vulnerability dimensions: Adaptive Capacity of the Social System (ACSS), Dependency on Fishing (DF), Dependency on Tourism (DT), Exposure of the Social System to Ecological Vulnerability (ESS), Fishing Pressure (FP), Pressure from Local Recreational Activities (LRP), Pressure from Non-Local Recreational Activities (NLRP) and

Recovery Potential of the Fish Community (RFC). The color gradient from light violet to dark violet shows the gradient from lower to higher SEV.

5.5. Discussion

To identify the areas that should be prioritized for management actions that foster resilience has become essential to mitigate and adapt to changes in the Anthropocene (Thiault et al., 2017; Silva et al., 2019). By assessing the SEV of temperate coastal systems to multiple pressures, we can identify areas with less capacity to cope with disturbances and where urgent management interventions are needed to build resilience (Adger, 2006). Our results demonstrate that different dimensions contribute to SEV, highlighting the need for distinctive management interventions in order to conserve and build resilience of coastal systems in temperate regions.

5.5.1. Advancing the operationalization of the SEV framework in temperate coastal systems for fishing and tourism

Our results demonstrated that the SEV framework, which was originally designed for climate change, can be operationalized to assess the vulnerability to other drivers of change such as fishing and tourism. To our best knowledge, this is an innovative application since most of SEV research in coastal systems have focused on tropical systems and climate change (Allison et al., 2009; Morzaria-Luna et al., 2014; Bennett et al., 2016; O'Higgins and O'Dwyer, 2019). The emphasis on tropical systems and climate change has responded to the emergency to halt biodiversity loss in these important *hotspots* of species richness (Partelow et al., 2017). However, recent studies demonstrate that temperate regions are *hotspots* of functional diversity (Stuart-Smith et al., 2013) and, as such, they also require scientific attention to foster their conservation. Our study advances the understanding of the SEV in temperate regions to build resilience in these areas.

We identified the SEV of temperate coastal systems to fishing and tourism pressures and unraveled the key social and ecological dimensions underpinning this vulnerability. First, we have extended the application of

SEV beyond tropical areas and climate change, through assessing SEV to fishing and tourism in the Spanish coastal system. We found that those areas with a high dependency on one single industry, i.e., tourism or fishing, are more likely to present higher SEV than other areas. For example, high dependency on tourism determined the high SEV of "Las Palmas" and "Santa Cruz de Tenerife". Both provinces are among the most popular tourist destinations in the European Union hosting more than 13,000,000 foreign tourists per year (Eurostat, 2019). We also found that the interlinkages between SEV dimensions are essential to understand the vulnerability of coastal systems. For example, the Balearic Islands are also highly dependent on tourism and have similar recovery potential of the fish community to "Las Palmas" and "Santa Cruz de Tenerife", yet its higher adaptive capacity of the social system lessens its SEV. By assessing SEV to fishing and tourism, we are also able to unravel which coastal regions are more threatened by both pressures. For example, Malaga does not show a high dependency on a unique industry (tourism or fishing), yet it presents a high SEV. This province hosts an important fishing heritage since Phoenician and Roman times, with archeological records along its coastline (Consejería de Agricultura y Pesca, 2007). However, in the 60s with the Spanish touristic "boom", Malaga also stood as a significant tourism destination (Mellado, 2013). Nowadays Malaga withstands moderate dependency on both tourism and fishing industries but the relatively low adaptive capacity of the Malaga social system and the low recovery potential of the fish community accounted for its high SEV.

Second, we have advanced the study of SEV in coastal systems by including different biodiversity metrics (species richness and functional diversity) in the assessment of the recovery capacity of the ecological system. Several researchers have included species richness in SEV assessments. For example, Cinner et al. (2013) and Siegel et al. (2019) included coral species richness and fish species richness in their studies to assess the recovery potential of the fish community. Cinner et al. (2013) also included the diversity of herbivores, representing one of the first studies including functional traits information when assessing SEV. Yet, recent studies have shown that different biodiversity metrics may respond differently to socio-economic factors (Lazzari et al., 2020). For example, whereas species richness is more associated with the type of territorial uses (i.e., natural land uses and protected surface), functional diversity is more associated with economic aspects (i.e., annual income per inhabitant and employment rate) (Lazzari et al., 2020). Therefore, we argue that integrating multiple biodiversity metrics is essential to assess SEV.

5.5.2.Management implications of SEV assessment

By assessing why some regions have low SEV, we can ascertain the management actions that lead to resilience. Since SEV and social-ecological resilience are opposing concepts that are strongly related (Folke et al., 2002; Gallopi, 2006; Miller et al., 2010), the identification of those dimensions that characterize low SEV provinces would point to key actions to increase the resilience of the coastal system. Our results suggest that management interventions oriented to reduce the dependency on tourism and fishing, increase the adaptive capacity of the social system, and reduce the pressure from both industries over the ecological system, may enhance the social-ecological resilience. In addition, our results suggest that those provinces with high pressure from local recreational activities show lower SEV. This result might prove that management plans that consider local recreational activities that foster a relationship to the proximal coastal system are essential for building social-ecological resilience (Davidson-Hunt and Berkes 2003; González et al., 2008; Blázquez-Salom et al., 2019).

“La Coruña” and “Pontevedra” were the most social-ecological vulnerable provinces. The high dependency on fishing, the low recovery potential of the fish community, and the high pressure from fishing activities were the factors contributing to their high SEV. Spain has 11 marine protected areas oriented to manage fishing resources under national jurisdiction, but almost 75% are located in the Mediterranean Sea and none of them are in the northwestern Spanish Atlantic coast (Sanabria-Fernandez et al., 2019). “La Coruña” and “Pontevedra” count with less than 6% of their coastal system protected under regional policies. Therefore, increasing efforts to protect northwest Spain considering its social-ecological characteristics seems to be an alternative to increase the recovery potential of the fish community (Franke et al., 2020). Besides, “La Coruña” and

"Pontevedra" present a long tradition of marine resource exploitation, being a significant fishing region for Spain and the European Union (Villasante et al., 2008; Pita et al., 2018). For these regions, we suggest to promote livelihood diversification, since it may reduce the high dependency on fishing and, therefore, reduce their SEV. One way to diversify livelihoods is to promote tourist activities that are related to the culture and marine heritage. In fact, fishing-tourism represents the first action for the economic diversification of fisheries in Spain (BOE nº 313, 27 December 2014; Piñeiro-Antelo and Lois-González, 2019). However, the implementation of such measures must be done with caution, as tourism is also an important pressure for marine biodiversity (Blancas et al., 2010; Bennett, 2018; de Andrés et al., 2018).

The uncontrolled coastal urbanization associated with tourism and the increased population during the peak season are important pressures for marine biodiversity (Blancas et al., 2010). Our results showed that, even with high ecological recovery potential of the fish community, "Las Palmas" and "Santa Cruz de Tenerife" showed high SEV. The high dependency on tourism, the low adaptive capacity of their social system and the high pressure from recreational activities contributed to increasing their SEV. National and international policy agendas are struggling to encourage the restructuration of the tourism industry towards eco-friendlier activities that foster the economic development of local communities minimizing the impacts in marine ecosystems, e.g., Sustainable Development Goals 8, 12, and 14, or the European Commission in its Agenda for a sustainable and competitive European tourism (Blancas et al., 2010; Blázquez-Salom et al., 2019). Besides, management interventions oriented to reduce the SEV by increasing the adaptive capacity of the social system of tourism-dependent provinces should i) develop innovative tourism alternatives such as ecotourism, ii) encourage community participation in planning processes, iii) boost the local economy through job creation and use of local products, and iv) foster environmental education programs (Muganda et al., 2013; Bello et al., 2016; Thetsane, 2019).

5.5.3. Limitations of the study

We focused on fishing and tourism as the main impacted and impacting industries, yet other activities may also affect coastal systems and conditioning their SEV (Thiault et al., 2017, 2019b). For example, the Mediterranean province of "Murcia" has the "Mar Menor", one of the largest coastal lagoons in the Mediterranean Sea. After decades of suffering the cumulative impact of anthropogenic activities, the Mar Menor collapsed in 2019 without recovery expectations (Crespo, 2019). Surprisingly, despite this province has recently suffered the social-ecological collapse of its coastal lagoon, our findings showed that "Murcia" had low SEV. The main reason for the collapse in the Mar Menor was the excess of nutrients and pollutants from intensive agriculture (Conesa and Jiménez-Cárceles, 2007), drivers of change that we did not address in this study. A broader application of this framework to explore the impacts of additional pressures such as agriculture may help to understand the SEV of coastal systems.

Furthermore, even though this study focused on the SEV assessment of coastal systems to fishing and tourism, we recognized the interconnection between the impact of these pressures at the local scale and the global drivers underpinning both pressures such as global trade and governance (Díaz et al., 2019). Telecoupling processes, i.e., socio-economic and environmental interactions between human-nature systems over long distances and across scales (from local to global, Liu et al., 2013; Martín-López et al., 2019), have reconfigured fishing and tourism industries. For example, Carlson et al. (2020) recently found that the study of social-ecological interactions along spatial and temporal scales may help to understand the underlying fishing fluxes, integrate the social-ecological complexities for better governance, and foster fisheries sustainability from local to global. Díaz et al. (2019) reported that the European Union, the United States, and Japan, together accounted for ~64% of the global fish imports, whereas those middle- and lower-income regions (according to World Bank income classification) accounted for 59% of the total volume of traded fish. These exchanges are mainly controlled by a handful of transnational corporations (Osterblom et al., 2015). This example shows that although the vulnerability to fishing is experienced at local and national scales, the drivers of change behind fishing trade operate on a global scale. Future research on SEV should consider the telecoupling processes by which global drivers cause local impacts on coastal systems.

5.6.Conclusions

Our findings contribute to the understanding of the social-ecological vulnerability (SEV) of coastal systems. By applying the SEV framework to the Spanish coastal system, our research advanced the study of SEV of temperate coastal systems to fishing and tourism. We detected priority areas where management actions were needed and we identified the strengths and weaknesses that contribute to SEV. Our results reveal that high dependency on one single industry, i.e., tourism or fishing, are more likely to present higher SEV, suggesting that the livelihood diversification is a possible strategy to reduce vulnerability. Furthermore, based on the knowledge gaps of this study, we suggest that future SEV assessment of coastal systems should include land-based pressures such as agriculture, and consider telecoupling processes across places. This research defines the SEV framework as a promising tool, not only to spatially detect SEV *hotspots*, but also to identify the key social and ecological dimensions underpinning vulnerability, and whose management may lead to increase the resilience of coastal temperate systems.

General discussion

Picture: School of Pompanos *(Trachinotus ovatus)* in Fuerteventura (Canary Islands, Spain) by Natali Lazzari

6

General discussion

The cumulative impact of human activities on natural systems has led our planet into the Anthropocene era. This geological period highlights the strong relationships between the human and the natural dimensions that set the basis for social-ecological systems (SES; Berkes and Folke, 1998; Liu et al., 2007; Ostrom, 2009). Knowing how both social and ecological dimensions are interconnected may inform future capacity-building efforts and other management actions oriented to the conservation of marine biodiversity (Leslie et al., 2015; Martín-López et al., 2017). The findings presented in this thesis contributed to advance in our understanding of the coastal and marine systems (hereafter coastal systems) of temperate regions, one of the less-studied SES in the world. Applying innovative methods, my research set the basic necessary knowledge for untangling the complex crossroad of this SES, providing a larger framework for preserving the rich biodiversity of this geographic region of the world.

6.1.Building up coastal and marine social-ecological knowledge

The operationalization of social-ecological frameworks is one of the major drawbacks for the integrated management of coastal systems (Martín-López et al., 2017; Thiault et al., 2017; Partelow, 2018). The reasons underpinning this challenge are manifold, such as the absence of a methodological framework that takes into consideration social and biophysical empirical data, the combined effect of different stressors, or the lack of methods that spatially identify social-ecological associations.

The Anthropocene is calling for interdisciplinary approaches, where research methodologies and empirical data from multiple disciplines come together for better informing the management of coastal systems (Leenhardt et al., 2015; Guerrero et al., 2018). There are numerous qualitative approaches to studying SES. From social-ecological frameworks based on the use of single resources to those oriented towards assessing the extent of external impacts (Berkes and Folke, 1998; Ostrom 2009; Marshall et al., 2009). Over 50% of the SES studies have a strong theoretical component and the operationalization of those frameworks persists underexplored (Rissman and Gillon, 2017; Partelow, 2018). In coastal systems, MacNeil and Cinner (2013) conducted one of the first attempts to operationalize SES frameworks including quantitative data when analyzing SES. They focused on the combination of socioeconomic and institutional information to assess SES but neglected the integration of the biophysical aspects of SES. This widespread pattern of focusing SES studies on social aspects, i.e., governance, socioeconomic, or resource management, required an urgent integration of biophysical information (Rissman and Gillon, 2017). In Paper I, I integrated social variables on demographics, economics, land uses, fishing activity, and nature protection with biophysical variables describing inorganic carbon concentration, primary productivity, nutrients concentration, salinity, and sea surface temperature. I applied multivariate techniques to unravel those areas characterized by similar social-ecological associations, where decision-makers should implement analogous management practices. In Paper I, I used an interdisciplinary methodological approach that overcame the challenge of integrating social and biophysical information, providing a practical tool for operationalizing SES frameworks and identifying social-ecological associations in marine and coastal systems.

Assessing social-ecological associations may also give insights for building resilience. One mechanism to increase social-ecological resilience is to reduce the vulnerability of the social-ecological associations (Marshall et al., 2009). The implementation of vulnerability frameworks faces difficulties in understanding the joint effect of multiple stressors and in integrating variables from several dimensions. The operationalization of most of the social-ecological vulnerability (SEV) frameworks pursues the specific assessment of one single and global impact, i.e., climate change (Cinner et al., 2012; Thiault et al., 2017; Mazor et al., 2018). Lack of information about the combined effect of more local stressors may hinder relevant knowledge for understanding social-ecological dynamics and how systems respond to local drivers of change, which is essential for effective management. Paper III evaluated the SEV to two local stressors (i.e. fishing and tourism pressures) and included methodological improvements for integrating social-ecological variables. Rather than evaluating how climate change may affect the vulnerability of both industries, we investigated how fishing and tourism may act by themselves as local impacts affecting social-ecological dynamics. We found that those areas with low recovery capacity of the ecological system, low social adaptive capacity, and moderate ecological exposure presented high SEV to fishing and tourism, even when they were moderately dependent on both industries. Increasing the social adaptive capacity and the ecological recovery capacity of those areas is a priority to foster social-ecological resilience. Contrary to previous studies that generated vulnerability indexes based on adding normalized variables, I developed a new approach to unveil the dominant relationships between variables (Thiault et al., 2017, Metcalf et al., 2015). The approach in Paper III relied on the application of multivariate analyses to identify the multiple dimensions of the SEV, removing potential biases associated with the simple addition of normalized variables. Besides making progress in our understanding of the SEV to local stressors, Paper III contributed to building up understanding about the social-ecological resilience of coastal systems through methodological improvements for the operationalization of the SEV framework, which can have even broader applications.

Understanding social-ecological associations is essential but insufficient for the management of coastal systems. Knowing how these social-ecological associations distribute spatially is crucial for managers and policy-makers (Thiault et al., 2017). Several studies focused on mapping human uses and their impacts on marine systems. For example, Sousa et al. (2016) designed a methodological framework for mapping ecosystem services in complex coastal regions, and Halpern et al. (2008) listed the most impacted marine ecosystems of the world mapping the cumulative impact of anthropogenic activities. However, a common method to spatially represent social-ecological associations remains challenging (Hanspach et al., 2016; Martín-López et al., 2017). Paper I addressed this issue and provided a common methodological approach to spatially identify coastal and marine social-ecological associations. Its implementation to the Mediterranean coast of Andalusia evidenced 12 coastal and marine SES representing areas with similar associations between socioeconomic and marine environmental characteristics. The spatial representation of social-ecological associations may also inform about priority areas for building up resilience (Halpern et al., 2015; Thiault et al., 2017). In Paper III we identified those Spanish provinces with high SEV where decision-makers have to prioritize management actions to improve resilience, such as A Coruña and Pontevedra. By defining and spatially identifying social-ecological associations, Papers I and III contributed to building up spatially explicit social-ecological knowledge of temperate coastal systems and offered methodological approaches to promote social-ecological evidence-based management.

6.2.Social-ecological assessments for biodiversity conservation

Unsustainable use of marine resources is threatening the world's marine biodiversity on which the future of coastal systems relies (Agardy et al., 2005). Biodiversity plays an important role in the maintenance of ecosystem functions and resilience. Coastal and marine SES must cope with such future biodiversity challenges, emphasizing the need for interdisciplinary approaches to reducing biodiversity loss (Luypaert et al., 2020). However, there are still numerous uncertainties about the role of marine biodiversity in SES and its implications for conservation, such as to what extent biodiversity is related to social and ecological variables, or how biodiversity metrics can inform decision-makers to strengthen the resilience of coastal and marine SES.

Marine biodiversity has become a conservation priority under numerous international strategies, yet the inclusion of biodiversity aspects when assessing social-ecological associations is still lacking (Rissman and Gillon, 2017). Since biological communities are strongly related to environmental conditions, coastal and marine SES identification indirectly comprises biodiversity characteristics (Paper I). The coastal and marine SES identified on the Mediterranean coast of Andalusia fit with the biogeographic regions of macrophyte diversity described by Bermejo et al. (2015), which were not included in the Paper I analysis of coastal and marine SES. The overlapping results of Paper I with those found by Bermejo et al. (2015) demonstrates that marine biodiversity results from the combination of several factors including marine environmental conditions.

Despite biodiversity is indirectly included in social-ecological assessments (Leslie et al., 2015, Mahboubi et al., 2015), Paper II provided evidence that biodiversity metrics are directly interlinked with socioeconomic variables. Socioeconomic variables gauge the human activities that can regulate marine biodiversity (such as fishing or land-use change) and are therefore key for biodiversity conservation. Fish biodiversity is highly dependent on fisheries, where human consumption is an essential piece to manage the overfishing puzzle (Quaas et al., 2016). Socioeconomic aspects such as market demand for fish regulate the fishing extent and, consequently, influence marine biodiversity (FAO, 2018; Friedman et al., 2018). Similarly, unsustainable land uses negatively impact marine biodiversity inducing, for example, water pollution (Alonso Roldán et al., 2015; Álvarez-Romero et al., 2015). Results of Paper II demonstrated the need for various management interventions based on the association between biodiversity metrics and socioeconomic aspects. For example, measures focused on regulating anthropogenic activities, reducing agricultural wastes, and increasing natural protection were most relevant to increase the biological diversity of coastal and marine SES with high agriculture-derived pollution and low natural protection. This interdisciplinary approach is starting to be implemented through ecosystem-based marine spatial planning. Ecosystem-based marine spatial planning represents an attempt to use the understanding of social-ecological associations for the management of human uses maintaining biodiversity and ecosystem functioning (Frazão Santos et al., 2019). Paper II showed evidence that efficient conservation relies on both social and biological information. The inclusion of biological information was as important as the consideration of social-ecological variables when assessing the biodiversity of SES.

The inclusion of complementary biodiversity metrics in social-ecological assessments can assess to what extent biodiversity conservation achieves its goals, providing insights for future conservation efforts (Stuart-Smith et al., 2013; Mouillot et al., 2014; Olivier et al., 2018). Paper II highlighted the variety of differential associations between socioeconomic and environmental variables with biodiversity metrics such as species and functional diversity. Thus, the focus on different biological aspects of the communities is critical for the management of coastal systems. Species diversity is a crucial indicator for assessing biodiversity (Gaston, 2000; Hillebrand, 2004) but it does not address functional aspects of the community (Duarte, 2000). Conversely, functional diversity addresses functional aspects of the community that are essential for understanding ecosystem functioning and resilience. Therefore, knowing how functional and species diversity relate to socioeconomic variables is critical to making efficient management decisions to achieve biodiversity goals (Strong et al., 2015; Rincón-Díaz et al., 2018; Ceulemans et al., 2019; Pimiento et al., 2020). For example, Paper II showed evidence that coastal and marine SES characterized by a high percentage of protected areas failed in protecting functional diversity. This result is consistent with recent studies conducted in the Mediterranean that demonstrate that the effectiveness of marine protected areas is lower for functional diversity than for other biological indicators such as biomass (Guilhaumon et al., 2015; Sanabria-Fernandez et al., 2019). Surprisingly, although the establishment of marine protected areas responds to several conservation goals, from fish stock restoration to protection of endangered species, all of them neglect the establishment of more resilient ecosystems, i.e., healthy ecosystem functioning (Sanabria-Fernandez et al., 2019). Future conservation efforts, including the specific association between socioeconomic variables and biodiversity metrics, may lead to more targeted policy and management interventions that result in enhanced resilience and more effective biodiversity conservation.

The more resilient a system is, the more opportunities it has to cope with disturbance (Folke et al., 2004). Reducing SEV may be essential for building up resilience and avoiding social-ecological collapse (Thiault et al., 2017). Social and ecological components are closely affected by global and local impacts, that altogether can strongly affect biodiversity and systems resilience (Díaz et al., 2015). Although several studies have examined the SEV of marine systems, most of them focused on tropical regions (Allison et al., 2009; Mozaria-Luna, 2014; Metcalf et al., 2015; O'Higgins and O'Dwyer, 2019). Tropical regions are widely known as a *hotspot* of species richness (Gaston, 2000; Bellwood and Huges, 2001; Hillebrand, 2004;). The number of marine species declines with increasing latitude, yet a new pattern rises when assessing functional diversity (Stuart-Smith et al., 2013). A higher number of functional diversity *hotspots* can be found in temperate regions, highlighting the importance of understanding the SEV of these regions. Paper III contributed to understanding the SEV of temperate regions through the operationalization of the SEV framework to temperate marine and coastal systems.

Besides the focus on tropical regions, the implementation of the SEV framework presents a strong human-centered perspective (Allison et al., 2009; Mozaria-Luna 2014; O'Higgins and O'Dwyer, 2019). For example, Cinner et al. (2012) and Marshall et al. (2013) focused mainly on the social dimension when assessing the SEV of coral reefs to climate-induced impacts. Whereas they studied the social sensitivity and social adaptive capacity to the impact, the understanding of the sensitivity and adaptive capacity of the ecological dimension remains underexplored. Biodiversity is essential to inform ecological adaptive capacity, as it increases the range of responses to disturbance (Bernhardt and Leslie, 2013). Yet, the use of biodiversity indicators to assess SEV is minimal (Thiault et al., 2017; Siegel et al., 2019). Indeed, the majority of the vulnerability studies that address the biological realm do so from a market perspective, i.e., these studies only include information on commercial species (Silva et al., 2019). The methodological approach for assessing SEV developed in Paper III advocates for the equal assessment and integration of social and ecological vulnerability and gives emphasis to biodiversity information. In this thesis, I used several diversity metrics to assess the ecological adaptive capacity, i.e., species richness and functional diversity, and all the social and ecological variables used to assess SEV had equal weights. This approach not only allowed us to identify the most social-ecological vulnerable areas but also to point to those social, ecological, or social-ecological components that need interventions should we aim to reduce SEV and promote social-ecological resilience.

The research in this thesis makes multiple contributions to the understanding of how biodiversity relates to social and ecological variables and how this relation may vary depending on the biodiversity metric used. Besides, I advanced the integration of biodiversity metrics when assessing SEV. In summary, this thesis showed multiple evidence for the need to include multiple biodiversity metrics in the interdisciplinary approaches that aim to reduce biodiversity loss and promote conservation.

6.3.Looking forward to the future of coastal and marine social-ecological systems: insights to overcome current challenges

Understanding social-ecological associations is a global priority for scientists and managers around the world. This thesis explores several tools for the spatial identification of coastal systems and the management implications related to each approach. Benefits and caveats unveiled along the current work may guide future social-ecological studies and underpin the integrated management of coastal systems.

First, one of the major limitations of social-ecological studies is data availability. Social-ecological approaches need social, economic, environmental, and biological information that may be difficult, expensive, and very time-consuming to obtain. I used open-source data from public databases such as those available in government, foundations, or altruist scientific websites, to facilitate the operationalization of social-ecological frameworks by managers (Paper I, II, and III). Information from open-sources helps us to get closer to social-ecological realities, but the use of primary information addressing local knowledge and local perceptions may bring us closer to the real complexity of SES (Pita et al., 2019; Planque et al., 2019). To assess the differences and similarities, the uniqueness and complementarities, and the actual strengths and weaknesses of such primary and secondary data sources when assessing SES should be a priority of the future agenda on SES research.

Second, the spatial scale of analysis is critical when assessing SES. SES operate on different spatial scales displaying level-specific dynamics, e.g., social-ecological associations at the municipality level might be different from those at the province level (Glaser and Glaser, 2014). Therefore, the spatial heterogeneity of social-ecological association may turn management approaches into dangerous traps (Dressel et al., 2018). In addition, the scale of governance is also critical for the management of SES (Lebel et al., 2006; Charles, 2012). The results of this thesis show that the design of management programs at the province level might be counterproductive because some coastal and marine SES are located across borders or because of the diversity of coastal and marine SES within a province (Paper I). Therefore, the integrated management of coastal areas should consider multi-scale approaches for the future assessment of coastal and marine SES and find a way to overcome the challenging coordination between all those institutions with coastal jurisdiction (Suárez de Vivero and Rodríguez Mateos, 2005; Barragán et al., 2008; Scholes et al., 2013).

Third, this thesis provides evidence for the spatial dynamics of coastal and marine SES based on a static picture of the social-ecological associations. Both social and ecological systems are subject to temporal changes (Glaser and Glaser, 2014; Dressel et al., 2018). Understanding the social-ecological associations over time may inform about temporal social-ecological trends and provide insights for predicting future social-ecological dynamics (Partelow, 2018; Santos-Martín et al., 2020). Besides, isolated advances in the temporal understanding of social-ecological associations are insufficient, thus the integrated management must be able to handle the changing coastal and marine SES (Glaser and Glaser, 2014; Dressel et al., 2018).

Fourth, in this thesis, I have demonstrated the importance of including marine biodiversity metrics when assessing SES (Papers II and III). I focused only on fish biodiversity inhabiting littoral rocky reefs because fish are the most diverse vertebrate group, are one of the major protein sources for humans, and are highly impacted by anthropogenic activities such as overfishing (Reynolds et al., 2005). However, future studies should also consider other taxonomic and functional groups and guilds, as well as different ecosystems, such as seagrass meadows. A comprehensive understanding of social-ecological dynamics related to different biodiversity metrics and ecosystems may be essential to the effective conservation of marine biodiversity.

Finally, important biodiversity problems loom in the Anthropocene. Both, global and local impacts threaten the future of marine biodiversity. Currently, there is a widespread trend of assessing SEV to global pressures such as climate change. In this thesis, I went beyond the assessment of global stressors and focused my research on SEV to local stressors such as fishing and tourism (Paper III). Yet, since the world is highly interconnected through global and local processes, studying intertwined social-ecological dynamics across spatial scales is a must. Telecoupling framework is a novel approach that tries to reduce this knowledge gap in ecosystem services research (Liu et al., 2013; Liu et al., 2019; Martín-López et al., 2019). It seems to be a promising framework to study the SEV of coastal systems to local and global stressors jointly. The role that the interactions between global and local biodiversity stressors may play when assessing SEV for marine biodiversity conservation loom large. This thesis just scratched the surface of what it certainly looks like an exciting future ahead of us, for both researchers and the environment.

Conclusions

Picture: School of Bastard grunts *(Pomadasys incisus)* in Fuerteventura (Canary Islands, Spain) by Natali Lazzari

7

Conclusions

The conclusions below are structured around three themes: theoretical and methodological contributions to social-ecological research (1, 2, 3, 4); implications for management and biodiversity conservation (5, 6, 7); and future research (8).

7.1. Theoretical and methodological contributions to SES research

The spatial assessment of SES can contribute to understanding the complexity of human-nature relations and the diversity of social-ecological associations in coastal systems. To do so, novel methodological approaches that spatially integrate information of both social and ecological dimensions to identify social-ecological associations are required. (*Paper I*)

The inclusion of biodiversity metrics when assessing SES is as important as considering environmental and socio-economic components. Accounting for the variety of differential associations between socioeconomic and environmental variables with biodiversity metrics, such as species and functional diversity, is essential to understand social-ecological dynamics (*Paper II*)

The understanding of coastal and marine SEV needs for unraveling the sensitivity, exposure, and adaptive capacity of social and ecological dimensions to the combined effect of local stressors. The operationalization of the SEV framework to local stressors provides priceless information for assessing the resilience of coastal and marine systems. (*Paper III*)

The use of social and biophysical empirical knowledge faces several challenges, from the limited data available to the absence of methodological frameworks that allow their integration. To overcome this challenge and advance the understanding of SES, the use of public databases and the development of integrative methodological approaches are crucial. (*Papers I-III*)

7.2.Implications for management and biodiversity conservation

The spatial characterization of SES in coastal and marine systems can contribute to identifying which management actions will be more effective in each SES, including environmental education programs, the control of agrochemical consumption in intensive agriculture, the promotion of organic agriculture, and the development of rules and norms that counteract current urban sprawl. (*Paper I*)

To unravel how socioeconomic and biophysical factors relate to marine biodiversity can help to design more specific management interventions to reduce biodiversity loss, such as fostering protected areas, or developing ecosystem-based management programs. (*Paper III*)

The identification of SEV *hotspots* is as essential as the identification of the social, ecological, or social-ecological components that underpin vulnerability. Both, the geographical identification of SEV *hotspots* and the identification of factors underpinning vulnerability, can contribute to informing planners and decision-makers about those areas that need urgent interventions to promote social-ecological resilience. (*Paper III*)

7.3.Future research

The operationalization of social-ecological frameworks provides the foundation for identifying the coastal and marine social-ecological associations. Yet, several challenges hamper the advances in social-ecological studies. Exploring and overcoming those priority drawbacks should guide the future study of coastal and marine SES. Future research challenges include: i) assessing strengths and weaknesses of using primary and secondary data sources; ii) integrating multi-scale approaches; iii) understanding temporal variations of social-ecological associations; iv) assessing social-ecological dynamics in multiple marine ecosystems; v) evaluating the combined effect of local and global impacts on the sustainability of coastal and marine SES. Future of social-ecological research should focus on the above mentioned knowledge gaps in order to effectively inform sustainable management of coastal and marine systems. (*Papers I-III*)

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Picture: School of Longspine snipefish *(Macroramphosus scolopax)* in Fuerteventura (Canary Islands, Spain) by Natali Lazzari

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Appendices

Picture: School of White trevally *(Pseudocaranx dentex)* in Fuerteventura (Canary Islands, Spain) by Jose A. Sanabria-Fernandez

Appendix for Chapter I. Supplement for materials and methods, and results sections

Table S1. Type and specific marine environmental variables used in this study with arguments for their selection

Type	Variables	Justification
Inorganic carbon	Mean calcite	This inorganic form of carbon has a large influence on the carbon cycle and biogenic calcification (Andersson et al., 2006; Borges and Gypens, 2010; IPCC, 2014)
Productivity	Mean chlorophyll a Minimum chlorophyll a	Chlorophyll is a physical environmental driver widely used as a proxy for phytoplanktonic productivity (Nguyen et al., 2011; Leslie et al., 2015)
Nutrients	Mean nitrate Mean phosphate	Nitrate and phosphate are limiting nutrients in marine ecosystems, but in excess, they could cause water eutrophication and hypoxic conditions and contribute to ocean acidification (Howarth, 2008; Crain et al., 2009)
Salinity	Mean salinity	Salinity is a key physiological factor; it can cause immediate mortality or sublethal stress at the organismal level, leading to shifts in community and ecosystem structures. In addition, salinity has strong implications in marine infectious diseases (Crain et al., 2009; Burge et al., 2014)
Temperature	Maximum SST Mean SST SST range	Sea surface temperature is an essential environmental characteristic that influences animal physiology, species distribution, coastal productivity, ocean acidification and infectious diseases (Floeter et al., 2005; Harley et al., 2006; Nguyen et al., 2011; Burge et al., 2014; Hiddink et al., 2015)

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Table S2. Units, years and sources of the marine environmental and socioeconomic variables used in our study. Marine environmental layers (Bio-ORACLE), Andalusian Multi-Territorial Information System (SIMA), Public Service State Employment (SEPE) and Ministry of Agriculture, Fisheries and Food (MAPA). PSS: practical salinity scale.

Type	Variables	Unit	Year	Source
Marine environment	Mean calcite	mol/m^3	2002-2009	Bio-ORACLE
	Mean chlorophyll a	mg/m^3	2002-2009	Bio-ORACLE
	Minimum chlorophyll a	mg/m^3	2002-2009	Bio-ORACLE
	Mean nitrate	mol/m^3	Various years	Bio-ORACLE
	Mean salinity	PSS	Various years	Bio-ORACLE
	Maximum SST	°C	2002-2009	Bio-ORACLE
	Mean SST	°C	2002-2009	Bio-ORACLE
	SST range	°C	2002-2009	Bio-ORACLE
	Mean phosphate	mol/m^3	2002-2009	Bio-ORACLE
Demographic	Population density	Ln (inhabitant km^{-2})	2016	SIMA
	Illiterate people	% of inhabitants	2011	SIMA
	People with a university degree	% of inhabitants	2011	SIMA
	People younger than 25	% of inhabitants	2016	SIMA
	People older than 65	% of inhabitants	2016	SIMA
Economic	People employed in primary sector	% of inhabitants	2016	SIMA
	People employed in secondary sector	% of inhabitants	2016	SIMA
	People employed in tertiary sector	% of inhabitants	2016	SIMA
	People who are unemployed	% of inhabitants	2016	SEPE
	Annual income per inhabitant	Ln (Euros)	2016	SIMA
	Tourist accommodations	N/coastline in km	2016	SIMA
Land use	Mountains	% of surface	2016	SIMA
	Meadows	% of surface	2016	SIMA
	Non-productive	% of surface	2016	SIMA
	Non-agricultural	% of surface	2016	SIMA
	Rivers and lakes	% of surface	2016	SIMA
	Crops	% of surface	2016	SIMA
	Fallow	% of surface	2016	SIMA
	Livestock	Individuals Ha^{-1}	2009	SIMA
Fishing industry	Catches	Tn/coastline in km	2016	SIMA
	Fishing vessels	N/coastline in km	2017	MAPA
	Fishers	% of inhabitants	2016	SIMA
Protection	Land protected area	% of surface	2016	MAPA
	Marine protected area	% of surface	2016	MAPA

Figure S1. Marine environmental variables obtained from Bio-ORACLE.

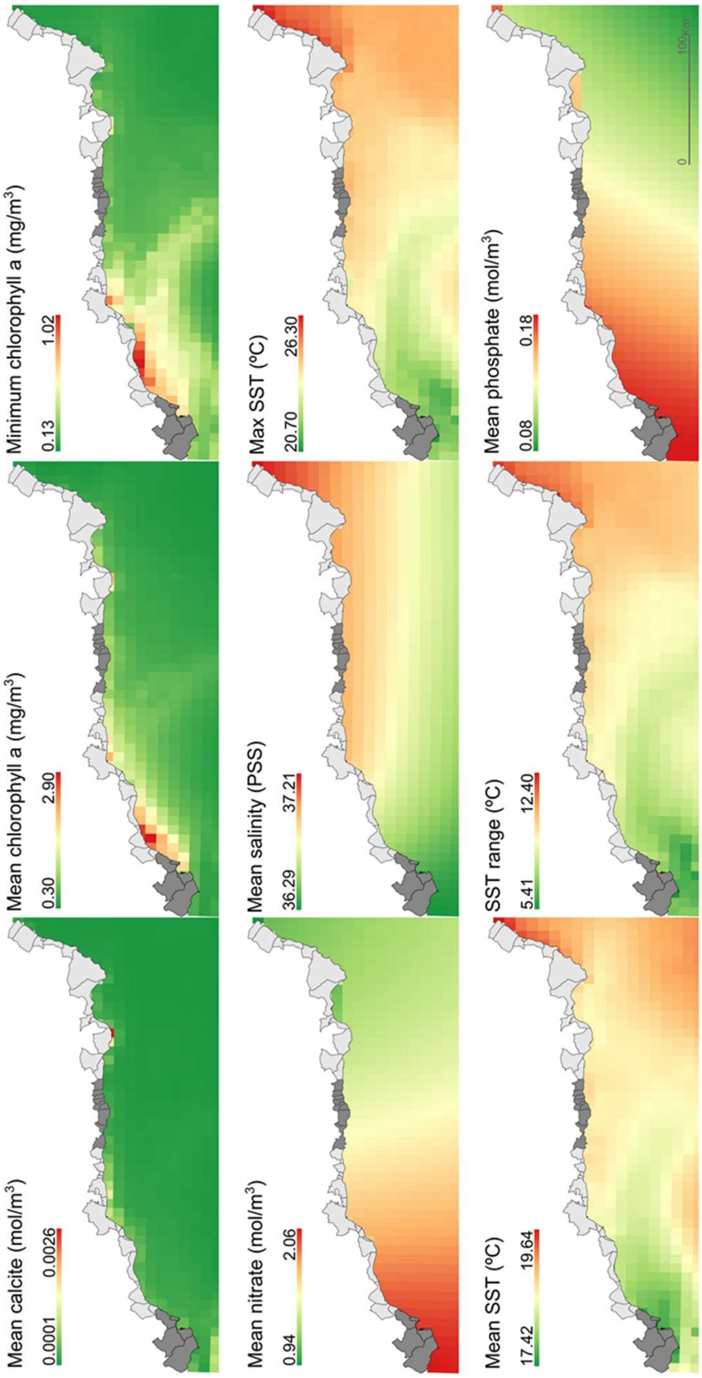


Table S3. Summary of the socioeconomic PCA showing the (a) eigenvalues and total variance, and (b) the factor loadings for the eight principal components. Items in bold denote a high factor loading (>0.5).

		PCA1	PCA2	PCA3	PCA4	PCA5	PCA6	PCA7	PCA8
(a)	Eigenvalue	3.18	2.81	2.70	2.54	2.36	2.06	1.73	1.41
	Proportion variance	0.13	0.12	0.11	0.11	0.10	0.09	0.07	0.06
	Cumulative variance	0.13	0.25	0.36	0.47	0.57	0.65	0.72	0.78
(b)	Population density	**0.62**	0.32	-0.33	-0.18	0.34	-0.27	0.30	-0.08
	Illiterate people	**-0.51**	0.47	0.07	0.04	-0.11	-0.19	-0.28	-0.35
	People with a university degree	**0.83**	0.03	-0.27	0.03	-0.02	-0.10	0.18	-0.04
	People younger than 25	0.12	**0.91**	-0.04	0.05	0.10	0.04	0.13	0.05
	People older than 65	-0.11	**-0.83**	-0.04	-0.06	-0.15	-0.12	-0.10	-0.14
	People employed in primary sector	-0.39	-0.24	**0.52**	-0.08	-0.22	-0.16	-0.30	0.38
	People employed in secondary sector	-0.03	0.20	0.02	0.14	-0.11	**0.89**	-0.02	0.16
	People employed in tertiary sector	**0.75**	0.07	-0.09	0.22	0.04	0.21	-0.21	0.25
	People who are unemployed	0.06	0.41	-0.23	0.29	0.19	-0.03	**0.58**	-0.30
	Annual income per inhabitant	0.09	-0.16	-0.47	-0.20	-0.26	**0.59**	-0.10	0.01
	Tourist accommodations	-0.05	0.20	0.08	0.04	-0.04	0.10	-0.05	**0.87**
	Mountains	-0.33	-0.12	0.15	**0.59**	-0.07	0.42	0.41	0.02
	Meadows	**-0.68**	-0.24	-0.22	-0.09	-0.07	-0.04	0.10	0.25
	Non-productive	0.11	0.39	**0.77**	0.01	0.07	-0.08	0.10	0.11
	Non-agricultural	0.08	0.19	0.41	0.01	0.35	0.00	**0.67**	0.00
	River and lakes	-0.32	-0.18	**0.67**	0.23	-0.24	0.13	0.09	-0.07
	Crops	-0.14	0.46	0.19	-0.23	-0.26	-0.44	-0.22	0.15
	Fallow	-0.25	-0.15	**0.73**	-0.34	0.12	-0.12	-0.04	0.03
	Livestock	**0.51**	-0.26	-0.27	-0.20	0.26	-0.08	0.02	-0.16
	Catches	0.19	0.14	-0.11	0.26	**0.77**	-0.15	0.09	0.04
	Fishing vessels	0.04	0.03	0.10	-0.18	**0.88**	-0.09	0.19	-0.05
	Fishers	0.05	0.10	0.08	0.38	**0.56**	0.25	-0.50	-0.14
	Land protected area	0.06	0.13	-0.03	**0.80**	0.07	0.41	-0.12	-0.07
	Marine protected area	0.10	0.01	-0.04	**0.90**	0.06	-0.20	0.08	0.08

Appendix for Chapter II. Supplement for study area, data collection and analyses, and discussion sections

Table S1. Characterization of the six CMSESs identified in the Andalusian coast (Lazzari et al., 2019).

	CMSES1	CMSES5	CMSES7	CMSES9	CMSES10	CMSES11
Location	Spread along ten municipalities located in the province of Granada and the western of the province of Almeria	Located in seven municipalities of the province of Malaga	Spread along the province of Almeria (two municipalities)	Spread along the provinces of Malaga (three municipalities) and Granada (one municipality)	Located in the provinces of Malaga (one municipality) and Almeria (one municipality)	Spread along the province of Granada (two municipalities) and Almeria (one municipality)
Surface (Km^2)	892.5	746.4	695.3	301.1	381.3	132.3
Human population	304,726 inhabitants in 2016. The average population density is 351.94 inhabitants per Km^2	1,044,042 inhabitants in 2016. The average population density is 2581.21 inhabitants per Km^2	36,397 inhabitants in 2016. The average population density is 64.76 inhabitants per Km^2	127,617 inhabitants in 2016. The average population density is 442.99 inhabitants per Km^2	215,719 inhabitants in 2016. The average population density is 452.93 inhabitants per Km^2	1,297 inhabitants in 2016. The average population density is 10.95 inhabitants per Km^2
Education (%)	4.31 people without studies and 6.78 people with a higher education	1.30 people without studies and 16.94 people with a higher education	3.33 people without studies and 7.77 people with a higher education	3.04 people without studies and 12.06 people with a higher education	2.68 people without studies and 14.30 people with a higher education	no people without studies and 2.59 people with a higher education
Age distribution (%)	27.87 people younger than 25 years old and 14.61 people older than 65 years old	26.13 people younger than 25 years old and 15.76 people older than 65 years old	29.37 people younger than 25 years old and 11.67 people older than 65 years old	25.05 people younger than 25 years old and 19.35 people older than 65 years old	25.45 people younger than 25 years old and 18.45 people older than 65 years old	12.98 people younger than 25 years old and 25.06 people older than 65 years old
Occupations (%)	15.56 agricultural and fisheries, 2.59 manufacturing and building, and 9.62 people unemployed	0.27 agricultural and fisheries, 3.21 manufacturing and building, and 9.59 people unemployed	15.94 agricultural and fisheries, 6.87 manufacturing and building, and 8.19 people unemployed	6.77 agricultural and fisheries, 3.12 manufacturing and building, and 10.37 people unemployed	2.30 agricultural and fisheries, 3.20 manufacturing and building, and 11.10 people unemployed	36.41 agricultural and fisheries, 3.73 manufacturing and building, and 6.03 people unemployed
Annual income	1,062.42 €	1,376.38 €	1,131.42 €	1,266.87 €	1,071.71 €	1,272.64 €
Surface utilization (%)	11.45 mountains, 6.83 non-productive, 9.34 non-agricultural, 1.95 river and lakes, and 12.41 fallow	0.07 fallow. Mountains, non-productive, non-agricultural, and river and lakes surface absent	16.26 mountains, 5.29 non-productive, 3.23 non-agricultural, 1.52 river and lakes, 0.52 fallow	0.17 mountains, 1.15 non-productive, 3.13 non-agricultural, 0.05 river and lakes, 0.61 fallow	10.07 mountains, 4.40 non-productive, 4.69 non-agricultural, 1.31 river and lakes, 0.06 fallow	26.80 mountains, 2.47 non-productive, 2.98 non-agricultural, 2.55 river and lakes, 14.11 fallow

	CMSES1	CMSES5	CMSES7	CMSES9	CMSES10	CMSES11
Surface protected (%)	1.52 terrestrial and marine protection absent	1.78 terrestrial and marine protection absent	60.46 terrestrial and 5.52 marine	0.51 terrestrial and 0.40 marine	42.56 terrestrial and 8.07 marine	Terrestrial and marine protection absent
Inorganic carbon (mol/m^3)	2.97E-04 mean calcite concentration	2.95E-04 mean calcite concentration	1.46E-04 mean calcite concentration	2.69E-04 mean calcite concentration	2.77E-04 mean calcite concentration	2.79E-04 mean calcite concentration
Primary productivity (mg/m^3)	0.83 and 0.26 mean and minimum chlorophyll a concentration, respectively	1.20 and 0.58 mean and minimum chlorophyll a concentration, respectively	0.40 and 0.18 mean and minimum chlorophyll a concentration, respectively	0.94 and 0.38 mean and minimum chlorophyll a concentration, respectively	0.79 and 0.28 mean and minimum chlorophyll a concentration, respectively	0.91 and 0.25 mean and minimum chlorophyll a concentration, respectively
Nutrients (mol/m^3)	1.39 mean nitrate concentration and 0.13 mean phosphate concentration	1.75 mean nitrate concentration and 0.16 mean phosphate concentration	1.19 mean nitrate concentration and 0.11 mean phosphate concentration	1.58 mean nitrate concentration and 0.15 mean phosphate concentration	1.36 mean nitrate concentration and 0.14 mean phosphate concentration	1.34 mean nitrate concentration and 0.14 mean phosphate concentration
Salinity (PSS)	36.93 mean salinity	36.77 mean salinity	37.01 mean salinity	36.90 mean salinity	36.94 mean salinity	36.95 mean salinity
Sea surface temperature (°C)	24.44, 18.67 and 9.81 maximum, mean and range of sea surface temperature, respectively	23.20, 18.35 and 8.32 maximum, mean and range of sea surface temperature, respectively	25.29, 18.99 and 10.96 maximum, mean and range of sea surface temperature, respectively	24.05, 18.65 and 9.22 maximum, mean and range of sea surface temperature, respectively	24.44, 18.69 and 9.83 maximum, mean and range of sea surface temperature, respectively	24.58, 18.67 and 10.02 maximum, mean and range of sea surface temperature, respectively

Table S2. Values of functional traits per species, which were used to calculate the functional alpha diversity metric (i.e., functional evenness), and fishing interest i.e., "Common", "Rare" or "None" indicating if the species is common, rare or inexistent in the fishing markets*.

Family	Species	Maximum length (cm)	Trophic group	Water column position	Habitat complexity	Gregariousness	Fishing interest
Serranidae	*Anthias anthias*	27	Higher carnivore	Demersal	Medium	Forming schools	Rare
Apogonidae	*Apogon imberbis*	15	Planktivore	Pelagic site attached	Medium	Forming schools	Rare
Atherinidae	*Atherina hepsetus*	20	Benthic invertivore	Pelagic non-site attached	Low	Forming schools	Rare
Sparidae	*Boops boops*	36	Benthic invertivore	Pelagic site attached	Low	Forming schools	Common
Balistidae	*Canthidermis sufflamen*	65	Benthic invertivore	Demersal	Medium	Solitary	Common
Labridae	*Centrolabrus exoletus*	18	Benthic invertivore	Demersal	Low	Solitary	None
Mugilidae	*Chelon labrosus*	75	Browsing herbivore	Pelagic site attached	Medium	Forming schools	Rare
Pomacentridae	*Chromis chromis*	25	Planktivore	Demersal	Medium	Forming schools	Rare
Labridae	*Coris julis*	30	Benthic invertivore	Demersal	Low	Paired	Rare
Labridae	*Ctenolabrus rupestris*	18	Benthic invertivore	Demersal	Low	Solitary	None
Moronidae	*Dicentrarchus labrax*	103	Higher carnivore	Demersal	Low	Forming schools	Common
Sparidae	*Diplodus annularis*	24	Benthic invertivore	Demersal	Low	Paired	Rare
Sparidae	*Diplodus cervinus*	43.5	Benthic invertivore	Demersal	Low	Paired	Rare
Sparidae	*Diplodus puntazzo*	60	Browsing herbivore	Demersal	Low	Paired	Rare
Sparidae	*Diplodus sargus*	43.5	Benthic invertivore	Demersal	Low	Paired	Rare
Sparidae	*Diplodus vulgaris*	45	Benthic invertivore	Demersal	Low	Paired	Rare
Engraulidae	*Engraulis encrasicolus*	20	Planktivore	Pelagic non-site attached	Low	Forming schools	Common
Serranidae	*Epinephelus costae*	140	Higher carnivore	Demersal	Medium	Solitary	Common
Serranidae	*Epinephelus marginatus*	150	Higher carnivore	Demersal	Medium	Solitary	Common
Gobiidae	*Gobius bucchichi*	10	Browsing herbivore	Benthic	Low	Solitary	None
Gobiidae	*Gobius geniporus*	16	Benthic invertivore	Benthic	Medium	Solitary	None
Labridae	*Labrus merula*	45	Benthic invertivore	Demersal	Low	Solitary	Rare
Labridae	*Labrus viridis*	47	Benthic invertivore	Demersal	Low	Solitary	Rare
Sparidae	*Lithognathus mormyrus*	55	Benthic invertivore	Demersal	Low	Forming schools	Common
Mugilidae	*Liza aurata*	59	Browsing herbivore	Pelagic non-site attached	Medium	Forming schools	Rare

Family	Species	Maximum length (cm)	Trophic group	Water column position	Habitat complexity	Gregariousness	Fishing interest
Mugilidae	*Liza ramada*	70	Browsing herbivore	Pelagic non-site attached	Low	Forming schools	Rare
Mugilidae	*Mugil cephalus*	100	Browsing herbivore	Pelagic site attached	Medium	Forming schools	Rare
Mullidae	*Mullus surmuletus*	40	Benthic invertivore	Demersal	Low	Paired	Common
Muraenidae	*Muraena helena*	150	Higher carnivore	Benthic	High	Solitary	Common
Sparidae	*Oblada melanura*	34	Benthic invertivore	Pelagic site attached	Low	Paired	Rare
Blenniidae	*Ophioblennius atlanticus*	19	Browsing herbivore	Benthic	Medium	Solitary	None
Sparidae	*Pagellus acarne*	36	Benthic invertivore	Pelagic site attached	Low	Forming schools	Common
Sparidae	*Pagellus erythrinus*	60	Benthic invertivore	Demersal	Low	Forming schools	Common
Blenniidae	*Parablennius incognitus*	5.8	Browsing herbivore	Benthic	Medium	Solitary	None
Blenniidae	*Parablennius pilicornis*	12.7	Browsing herbivore	Benthic	Medium	Solitary	None
Blenniidae	*Parablennius rouxi*	8	Browsing herbivore	Benthic	Medium	Solitary	None
Blenniidae	*Parablennius sanguinolentus*	20	Browsing herbivore	Benthic	Medium	Solitary	Rare
Haemulidae	*Parapristipoma octolineatum*	50	Benthic invertivore	Demersal	Medium	Paired	Rare
Phycidae	*Phycis phycis*	65	Higher carnivore	Benthic	High	Solitary	Common
Sparidae	*Sarpa salpa*	51	Browsing herbivore	Demersal	Medium	Forming schools	Common
Scorpaenidae	*Scorpaena porcus*	37	Higher carnivore	Benthic	Medium	Solitary	Common
Carangidae	*Seriola dumerili*	190	Higher carnivore	Pelagic non-site attached	Low	Paired	Common
Serranidae	*Serranus cabrilla*	40	Benthic invertivore	Demersal	Medium	Solitary	Common
Serranidae	*Serranus scriba*	36	Benthic invertivore	Demersal	Medium	Solitary	Common
Sphyraenidae	*Sphyraena viridensis*	128	Higher carnivore	Pelagic non-site attached	Low	Forming schools	Common
Centracanthidae	*Spicara maena*	25	Planktivore	Pelagic site attached	Medium	Forming schools	Common
Centracanthidae	*Spicara smaris*	20	Planktivore	Pelagic site attached	Low	Forming schools	Common
Sparidae	*Spondyliosoma cantharus*	60	Benthic invertivore	Demersal	Low	Paired	Common
Labridae	*Symphodus doderleini*	10	Benthic invertivore	Demersal	Medium	Solitary	None
Labridae	*Symphodus mediterraneus*	18	Benthic invertivore	Demersal	Medium	Solitary	Rare
Labridae	*Symphodus melanocercus*	14	Benthic invertivore	Demersal	Medium	Paired	None
Labridae	*Symphodus melops*	28	Benthic invertivore	Demersal	Medium	Paired	Rare
Labridae	*Symphodus ocellatus*	12	Benthic invertivore	Demersal	Medium	Paired	None
Labridae	*Symphodus roissali*	17	Benthic invertivore	Demersal	Medium	Solitary	Rare

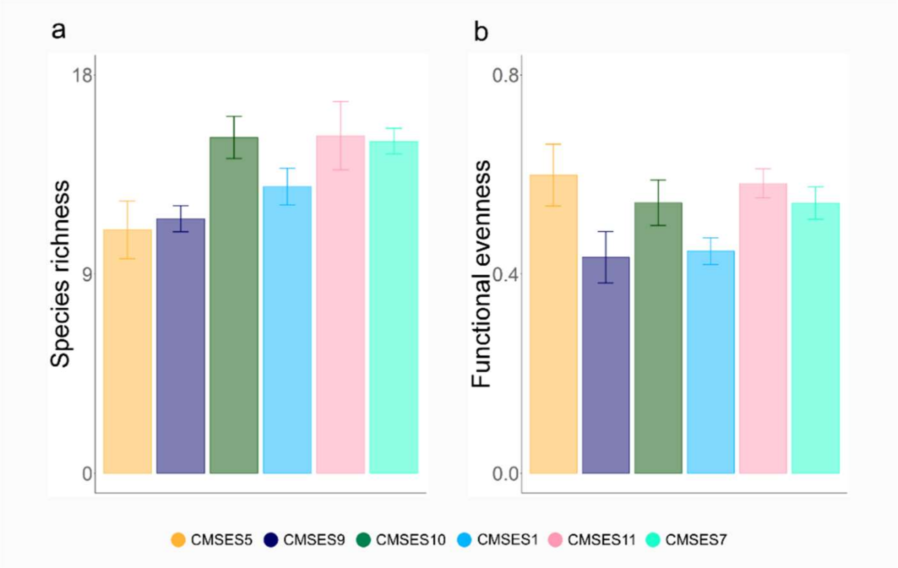
Family	Species	Maximum length (cm)	Trophic group	Water column position	Habitat complexity	Gregariousness	Fishing interest
Labridae	*Symphodus rostratus*	13	Benthic invertivore	Demersal	Medium	Solitary	None
Labridae	*Symphodus tinca*	44	Benthic invertivore	Demersal	Medium	Paired	Rare
Syngnathidae	*Syngnathus abaster*	21	Benthic invertivore	Benthic	Medium	Solitary	Rare
Labridae	*Thalassoma pavo*	25	Benthic invertivore	Demersal	Low	Paired	Rare
Trachinidae	*Trachinus draco*	53	Higher carnivore	Benthic	Low	Solitary	Common
Tripterygiidae	*Tripterygion delaisi*	8.9	Benthic invertivore	Benthic	Medium	Solitary	None

*Consejería de Agricultura y Pesca. Junta de Andalucía. 2001 Especies de Interés Pesquero en el Litoral de Andalucía, Sevilla.

Table S3. Summary of the socioeconomic PCAs showing the (a) eigenvalues and total variance, and (b) the factor loadings for the principal components. Items in bold denote a high factor loading (>0.6).

Socioeconomic aspect			PCA1	PCA2	PCA3
Demographic	(a)	Eigenvalue	2.68	1.58	
		Proportion variance	0.54	0.32	
		Cumulative variance	0.54	0.85	
	(b)	Population density	**0.85**	-0.33	
		Illiterate people	-0.06	**0.87**	
		People with a university degree	**0.79**	-0.52	
		People younger than 25	**0.83**	0.52	
		People older than 65	**-0.80**	-0.40	
Economic	(a)	Eigenvalue	2.13	1.36	1.26
		Proportion variance	0.36	0.23	0.21
		Cumulative variance	0.36	0.58	0.79
	(b)	People employed in primary sector	**-0.82**	0.31	0.15
		People employed in secondary sector	0.35	0.37	**0.79**
		People employed in tertiary sector	**0.81**	0.13	0.27
		Annual income per inhabitant	0.43	**0.69**	-0.20
		Tourists accommodation	0.50	0.21	**-0.70**
		People who are unemployed	0.50	**-0.76**	0.12
Land uses	(a)	Eigenvalue	2.22	2.20	1.73
		Proportion variance	0.28	0.28	0.22
		Cumulative variance	0.28	0.55	0.77
	(b)	Crops	0.38	0.03	**0.82**
		Fallow	0.24	**0.82**	0.05
		Mountains	0.16	0.54	-0.47
		Meadows	-0.45	**0.69**	0.04
		Non-productive	**0.93**	0.17	0.00
		Non-agricultural	**0.91**	0.17	0.14
		River and lakes	0.31	**0.84**	-0.10
		Livestock	-0.08	-0.04	**0.89**
Sea uses	(a)	Eigenvalue	1.91		
		Proportion variance	0.64		
		Cumulative variance	0.64		
	(b)	Landings	**0.94**		
		Fishing vessels	**0.86**		
		Fishers	0.54		
Environmental protection	(a)	Eigenvalue	1.55		
		Proportion variance	0.78		
		Cumulative variance	0.78		
	(b)	Land protected area	**0.88**		
		Marine protected area	**0.88**		

Figure S1. Mean values with error bars for the alpha diversity indices in each CMSESs: (a) species richness, (b) functional evenness. CMSESs ordered geographically from west to east.



Appendix for Chapter III. Supplement for methods and results sections

Table S1. Variables used in our study to assess social-ecological vulnerability. We included the vulnerability and index that they compose as well as the units, resolution, description, references, sources and years. Ministry of Agriculture, Fisheries and Food (MAPA), Public Service State Employment (SEPE), Spanish Statistical Office (INE), The Food and Agriculture Organization (FAO), Superior Sports Council (CSD), National Association of Nautical Companies (ANEN), Bajoelagua webpage (www.bajoelagua.com/buceo/), Reef Life Survey (RLS; www.reeflifesurvey.com), and Fishbase webpage (www.fishbase.de/). * indicate variables stemming from intrinsic calculations.

Vulnerability	Index	Variable	Unit	Resolution	Description	Reference	Source	Year
Social vulnerability	Exposure	Fishing industry exposure	N	Municipality	Average of ecological vulnerability within a buffer area of 12 nautical miles (distance from the coast were artisanal fisheries operate; Soltanpour et al., 2017) radius around each port.	Thiault et al., 2017	*	-
		Tourism industry exposure	N	Municipality	Average of ecological vulnerability within a buffer area of 100km radius around the geographical center of each municipality.	Martín-López et al., 2009	*	-
	Sensitivity	Fish consumption	%	CCAA	Percentage of annual fish consumption.	Siegel et al., 2019	MAPA	2015
		Employment on fishing industry	%	Province	Percentage of contracts on fishing industry.	Marshall et al., 2013; Senapati and Gupta, 2017; Siegel et al., 2019	SEPE	2015
		Employment on hotel industry	%	Province	Percentage of contracts on hotel industry.	Marshall et al., 2013; Metcalf et al., 2015; Moreno and Becken, 2009	SEPE	2018
		Tourist accommodation	N	Province	Number of hotel rooms.	Moreno and Becken, 2009	INE	2018
		Tourist room profit	€/day	CCAA	Profit per tourist room by day.		INE	2018
	Adaptive capacity	Multidimensional wealth	%	CCAA	Wealth measured by multiple dimensions i.e., ability to afford to pay for one-week annual holiday away from home, to afford a meal with meat, chicken, fish (or vegetarian equivalent) every second day, to keep home adequately warm, to face unexpected financial expenses, to pay all household expenses, to have a motor vehicle and to have a personal computer.	McClanahan et al., 2008; Cinner et al., 2013	INE	2017
		Unidimensional wealth	%	CCAA	Wealth measured by one dimension i.e., ability to make ends meet without difficulties	Acosta et al., 2013	INE	2018
		Literacy	%	CCAA	Inhabitants working or looking for job, who have finished, at least, elementary school	Acosta et al., 2013; Siegel et al., 2019	INE	2018
		Mobility in the primary sector	%	Province	Percentage of primary sector contracts that involve interprovincial displacement. Primary sector refers to agriculture and fishing.	McClanahan et al., 2008; Cinner et al., 2013	SEPE	2015
		Mobility in the tertiary sector	%	Province	Percentage of tertiary sector contracts that involve interprovincial displacement. Tertiary sector refers to services.	McClanahan et al., 2008; Cinner et al., 2013	SEPE	2015
Ecological vulnerability	Exposure	Fishing vessels	N/km	Municipality	Number of artisanal fishing vessels (<12m length; Quetglas et al., 2016) per km of coastline.	Thiault et al., 2017	FAO	2017
		Fishing vessel gross tonnage	GT/km	Municipality	The volume capacity of all artisanal fishing vessels (<12m length; Quetglas et al., 2016) per km of coastline. Gross tonnage is considered one of the most important predictors of fishing effort (Parente, 2004).	Thiault et al., 2017	FAO	2017
		Fish landings	Tn/km	Municipality	Tons of littoral fish landings per km of coastline.	Thiault et al., 2017	Various	2011-2015

Vulnerability	Index	Variable	Unit	Resolution	Description	Reference	Source	Year
		Licenses for recreational fishing	N/km	CCAA	Number of recreational fishing licenses per km coatline. This includes fishing activities in coastal systems such as coastal fishing or kayak fishing.	Davenport and Davenport, 2006	CSD	2018
		Licenses for underwater activities	N/km	CCAA	Number of of licenses for underwater activities per km coatline. This includes all aquatic sports in coastal systems, such as free diving, SCUBA diving, underwater photograpy or underwater fishing.	Davenport and Davenport, 2006	CSD	2018
		Recreational vessels registration	N/km	CCAA	Registration of new recreational vessels per Km of coastline.	Davenport and Davenport, 2006	ANEN	2015
		Dive centers	N/km	Municipality	Number of dive centers per km of coastline.	Riera et al., 2016	Bajoelagua	2016
		Tourism	N/km2	Province	Number of tourists per km2.	Moreno and Becken, 2009	INE	2018
		Dependency on fishing	N	Municipality	Dependency on fishing dimension of the *social sensitivity index*	Thiault et al., 2017	*	-
		Dependency on tourism	N	Municipality	Dependency on tourism dimension of the *social sensitivity index*	Thiault et al., 2017	*	-
	Recovery potential	Species richness	N	Sampling site	Number of fish species per sampling site.	Cinner et al., 2013	RLS	2015-2019
		Functional redundancy	N	Sampling site	Fish functional diversity based on Rao's quadratic entropy, which integrates several traits weighted by the relative abundances of species (Botta-Dukát 2005).	Bernhardt and Leslie, 2013; Cinner et al., 2013	RLS	2015-2019
		Resilience to fishing	N	Sampling site	Community-weighted mean of intrinsic resilience to fishing.	Thiault et al., 2017	Fishbase	2015-2019

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Table S2. Summary of the PCAs showing the (a) eigenvalues and total variance, and (b) the factor loadings for the principal components. Items in bold denote a high factor loading (>0.6).

Vulnerability	Index			PCA1	PCA2	PCA3	Dimensions
Social vulnerability	Exposure	a)	Eigenvalue	1.96			
			Proportion variance	0.98			
			Cumulative variance	0.98			
		b)	Fishing industry exposure	**0.99**			Exposure of the social system to ecological vulnerability
			Tourism industry exposure	**0.99**			
	Sensitivity	a)	Eigenvalue	2.42	1.93		
			Proportion variance	0.48	0.39		
			Cumulative variance	0.48	0.87		
		b)	Fish consumption	-0.67	**0.63**		Dependency on fishing
			Employment on fishing industry	0.00	**0.97**		
			Employment on hotel industry	**0.80**	-0.38		Dependency on tourism
			Tourist accommodation	**0.94**	0.08		
			Tourist room profit	**0.66**	-0.67		
	Adaptive Capacity	a)	Eigenvalue	3.39			
			Proportion variance	0.68			
			Cumulative variance	0.68			
		b)	Multidimensional wealth	**0.95**			Adaptive capacity of the social system
			Unidimensional wealth	**0.77**			
			Literacy	**0.71**			
			Mobility in the primary sector	**0.83**			
			Mobility in the tertiary sector	**0.84**			
Ecological vulnerability	Exposure	a)	Eigenvalue	2.45	2.44	1.41	
			Proportion variance	0.31	0.31	0.18	
			Cumulative variance	0.31	0.61	0.79	
		b)	Fishing vessels	**0.94**	-0.07	0.02	Fishing pressure
			Fishing vessel gross tonnage	**0.93**	0.09	0.07	
			Fish landings	**0.79**	0.07	-0.06	
			Licenses for recreational fishing	0.00	**0.90**	-0.32	Pressure from local recreational activities
			Licenses for underwater activities	0.12	**0.89**	-0.05	
			Recreational boats registration	-0.04	**0.90**	0.26	
			Dive centers	0.16	0.00	**0.71**	Pressure from non-local recreational activities
			Tourism	-0.17	-0.05	**0.87**	
	Recovery potential	a)	Eigenvalue	1.61			
			Proportion variance	0.54			
			Cumulative variance	0.54			
		b)	Species richness	**0.81**			Recovery potential of the fish community
			Functional redundancy	**0.79**			
			Resilience to fishing	**0.58**			

Published chapters

Picture: School of Swallowtail seaperch *(Anthias anthias)* in Peñón de Vélez de la Gomera (Spanish territories in the northern coast of Africa) by Natali Lazzari

Environmental Science and Policy 92 (2019) 56–65

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

Spatial characterization of coastal marine social-ecological systems: Insights for integrated management

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ARTICLE INFO

Keywords:
Andalusia
Human-Nature systems
Littoral areas
Marine spatial planning
Mediterranean Sea
Regional scale

ABSTRACT

Understanding the complexity of social-ecological systems is fundamental for achieving sustainability. Historically, humans have benefited from the ecosystem services offered by nature at the same time that natural systems have increasingly changed because of anthropogenic activities. The lack of methods to unveil and understand such associations might hinder the integrated management of coastal marine areas. In our study, we applied a methodological framework used in terrestrial systems to identify and spatially locate the coastal marine social-ecological systems (CMSESs) on the southern Mediterranean Spanish coast. These CMSESs represent areas with similar human-nature associations that result from sharing similar socioeconomic and marine environmental characteristics. We applied several multivariate analyses to identify and characterize these CMSESs. We found the presence of twelve CMSESs that suggest a co-evolution of the social-ecological associations in these areas. Our results highlight the need for integrated coastal planning and management that consider the specific characteristics and conservation challenges of each CMSES. Our study provides evidence that a successful methodological framework to identify and characterize social-ecological systems can be applied in coastal areas and contribute to integrated management for the sustainability of these fragile systems.

1. Introduction

Social-ecological systems are complex adaptive systems in which social and bio-geophysical dimensions interact on multiple temporal and spatial scales (Berkes and Folke, 1998; Liu et al., 2007; Ostrom, 2009). These social-ecological associations point to mutual dependencies between social and ecological components. While human activities such as pollution or habitat protection have an impact on ecological dynamics (e.g., Vitousek et al., 1997), natural processes such as extreme weather events influence the ecosystem services provided to society (Adger, 2005; Liu et al., 2007). Understanding the associations between ecological and social systems is particularly relevant in achieving sustainability (Glaser et al., 2012).

Coastal systems support the livelihood of a large and growing proportion of the world's human population (Agardy et al., 2005). Over centuries, human societies have benefited from the ecosystem services provided by coastal marine systems such as food from fisheries, regulation of natural hazards (e.g., tsunamis), and recreational or aesthetic experiences (Liquete et al., 2013; Martínez et al., 2007). However, coastal areas are also facing significant coastal erosion, pollution, and biodiversity loss (Cloern et al., 2016; Vitousek et al., 1997), which in turn have jeopardized the ecosystem services provided (Serrao-Neumann et al., 2016). To revert the degradation of coastal ecosystem services through more sustainable management actions, it is necessary to understand the complex associations that characterize social-ecological systems (de Andrés et al., 2017). The number of studies that have sought to understand social-ecological associations has increased in the last decade (Binder et al., 2013; Rissman and Gillon, 2016), particularly in coastal areas (e.g., Álvarez-Romero et al., 2011; Ban et al., 2013; Cinner et al., 2009). However, there is no empirical evidence on how these associations are expressed spatially, i.e., the spatial configuration of coastal marine social-ecological systems (CMSESs). Although some methodological approaches have been suggested for mapping coastal ecosystem services (Sousa et al., 2016) or human impacts on coastal

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https://doi.org/10.1016/j.envsci.2018.11.003
Received 29 May 2018; Received in revised form 5 November 2018; Accepted 5 November 2018

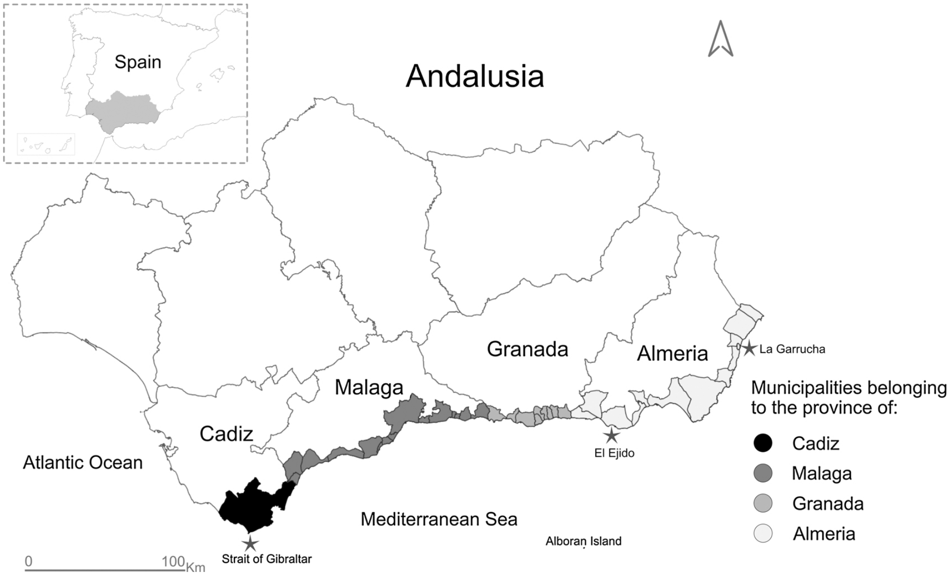

Fig. 1. Map of the study area on the Mediterranean coast of Andalusia. The map illustrates the geographical location of the coastal municipalities, which belong to the four Andalusian provinces of Cadiz (5 municipalities), Malaga (14 municipalities), Granada (9 municipalities), and Almeria (13 municipalities).

and marine systems (Ban et al., 2010; Halpern et al., 2009), few studies have developed methodological tools to spatially represent CMSESs, particularly at regional scales (Mahboubi et al., 2015). The lack of methodological developments to spatially characterize social-ecological associations at the regional scale is considered a major drawback of using the social-ecological system framework in management (Hanspach et al., 2016; Martín-López et al., 2017). In fact, the lack of empirical evidence on the spatial representation of CMSES can lead to their mismanagement (Liu et al., 2007; Rissman and Gillon, 2016).

In our study, we aim to spatially identify and characterize the social-ecological associations within CMSES by analysing the marine environmental and socioeconomic characteristics of coastal marine areas. We tested a methodological approach to identify and characterize CMSESs on the southern Mediterranean Spanish coast.

2. Materials and methods

2.1. Study area

The study area is located on the Mediterranean coast of Andalusia in southern Spain (Fig. 1). The 500 km-long coastal area investigated in our study spans over 41 littoral municipalities belonging to four Andalusian provinces (Cadiz, Malaga, Granada, and Almeria). The Andalusian shoreline includes a wide variety of land and sea uses, from natural protected areas such as the Natural Park of the Strait (Cadiz) to intensively managed lands and fishing areas such as the greenhouses of El Ejido and the littoral area of La Garrucha, respectively (both in Almeria; Fig. 1). Environmentally, the Mediterranean coast of Andalusia is also highly variable because the Mediterranean Sea is connected to the Atlantic Ocean in the west by the Strait of Gibraltar (Coll et al., 2010). Indeed, this region of the Mediterranean has unique oceanographic characteristics with the coldest, least saline, and most productive waters of the entire Mediterranean Sea due to the mixing of Atlantic and Mediterranean waters (Minas et al., 1991). In addition, the irregular underwater geography of the western Mediterranean Sea, with numerous canyons, anticyclonic areas, and an important shelf extension, promotes the existence of coastal upwellings that support high productivity (Pinardi et al., 2006; Sarhan et al., 2000). As a result, the marine area investigated in our study includes a wide variety of marine ecosystems, such as rocky reefs, seagrasses, soft bottoms and deep coral reefs. Due to these characteristics, the Mediterranean Sea is recognized as one of the world's marine biodiversity hotspots (Coll et al., 2010; Myers et al., 2000).

As in other areas of the world, rural Andalusian populations decrease as urban populations grow, particularly in coastal areas (Collantes and Pinilla Navarro, 2011; Garcia-Llorente et al., 2015). The Mediterranean coast of Andalusia hosts 9.70% of the Spanish population, which is almost five million inhabitants distributed throughout 4 provinces with a total surface of 36,167 km^2. The average unemployment rates exceed 10% in this area, with that in Cadiz reaching a peak of 15%. Almeria is the province with the highest percentage of illiteracy (2.80%), and Granada has the highest percentage of people with a university degree (16.10%). In all of these provinces, the tertiary sector (i.e., building, transport, and services) and the primary sector (i.e., agriculture, fishing, and livestock) contribute the highest and lowest income, 77.60% and 6.60% of the Andalusian Gross Domestic Product, respectively. The fishing sector employs almost 4500 inhabitants. The province of Cadiz has the highest number of professional boats per kilometre of coast and the largest fishermen's guild, followed by Malaga, Almeria, and Granada.

The current rise of the human population and urbanization of coastal areas (de Andrés et al., 2017) together with the over-exploitation of fisheries in the Mediterranean coast of Andalusia promote biodiversity loss, pollution, and the degradation of important habitats such as rocky reefs, seagrasses, and estuaries (Coll et al., 2010).

2.2. Data collection

Following the methodological approach developed by Martín-López et al. (2017) to identify terrestrial social-ecological systems, we collected marine environmental and socioeconomic data to identify and characterize the marine environmental and socioeconomic spatial classes that were homogeneous within but distinct among the social-ecological systems (Fig. 2). The marine environmental information was extracted from the satellite database Bio-ORACLE (Assis et al., 2018). To obtain the marine environmental data, we extracted the values of

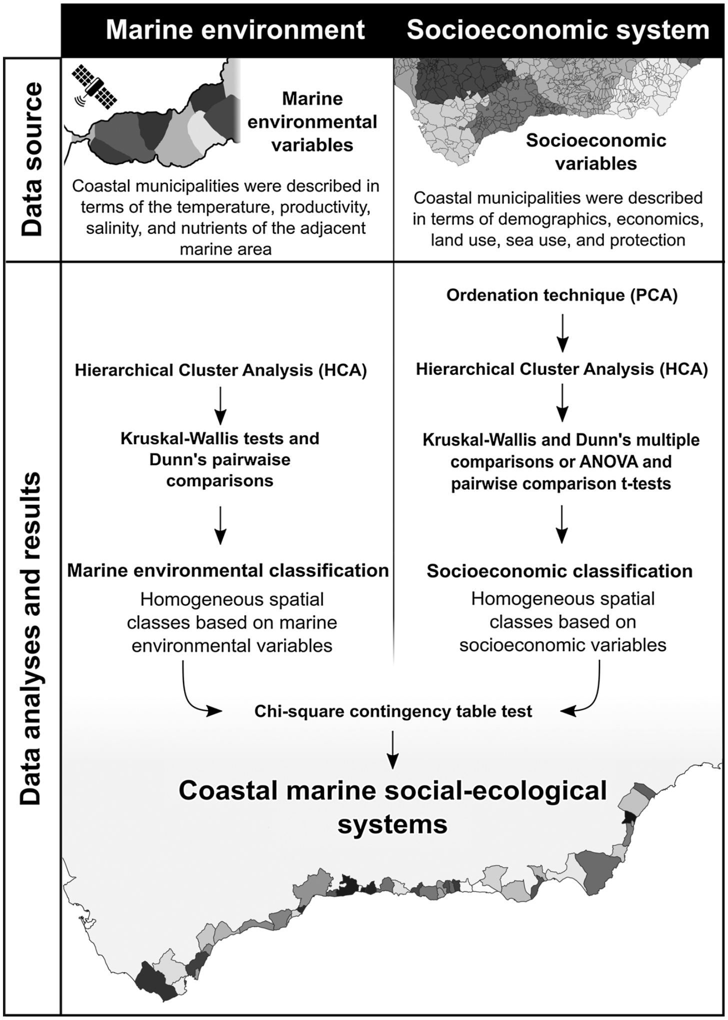

Fig. 2. Methodological approach used to identify and characterize the coastal marine social-ecological systems (CMSESs) in Andalusia. Adaptation from Martín-López et al. (2017).

nine variables from ocean pixels contiguous to the coastline with a 9.2 × 9.2 km resolution (the maximum resolution of the Bio-ORACLE database) (see Fig. S1 in Appendix A). We selected nine marine environmental variables that are essential for marine biodiversity (Stuart-Smith et al., 2013) (see Table S1 in Appendix A): inorganic carbon (calcite concentration), primary productivity (minimum chlorophyll *a* and mean chlorophyll *a*), nutrients (nitrate and phosphate concentrations), salinity, and sea surface temperature (maximum SST, mean SST and SST range). We averaged the pixel values for each municipality for each marine environmental variable to obtain a single marine environmental value per municipality.

We collected the socioeconomic information from three public databases: SIMA (Andalusian Multi-Territorial Information System, 2018), SEPE (Public Service State Employment, 2018), and MAPA (Ministry of Agriculture, Fisheries and Food, 2018). We collected socioeconomic information for the 41 municipalities located on the Mediterranean coastline of Andalusia. We selected the municipality as the most suitable organizational level to collect socioeconomic data because it is the most detailed administrative unit at which official statistics exist (Martín-López et al., 2017). We collected 24 socioeconomic variables at the municipal scale (see Table S2 in Appendix A). The socioeconomic information encompassed variables on demography, economic status, land use, fishing activity, and environmental protection. The demographic variables included population density, age (percentage of people younger than 25 years old and percentage of people older than 65 years old), and education level (percentage of people with university degree and percentage of illiterate people). The variables regarding economic status included income, the percentage of people employed in the primary, secondary, and tertiary economic sectors, the percentage of unemployed people, and the number of tourist accommodations per kilometre of coast. The variables conveying information on land use included information on natural surfaces (percentages of mountains, rivers, lakes, non-agricultural, and non-productive surfaces), agricultural surfaces (percentages of meadows, crops, and fallows), and livestock per Ha. We included land use information because land use changes in recent decades (intensification and rural abandonment) have been the main direct drivers of the changes in Spanish and worldwide ecosystems (MAGRAMA, 2014; Pereira et al., 2012). The fishing activity variables included tonnes of catches, the number of fishing vessels per kilometre of coast, and the percentage of people employed in the fishery sector. Finally, we also considered the level of environmental protection by including two variables: the percentages of land and sea surface covered by terrestrial and marine protected areas, respectively.

2.3. Data analyses

We followed a combination of two analytical approaches with the marine environmental variables and socioeconomic variables to characterize the Andalusian CMSESs (Fig. 2). First, we performed a principal component analysis (PCA) with varimax rotation on the socioeconomic data to simplify the dimensions of the socioeconomic variables and to unveil the dominant relationships among them. We selected the PCA components with an eigenvalue higher than 1, i.e., the Kaiser criterion (Kaiser, 1960). Second, we carried out two hierarchical cluster analyses (HCA), first HCA with the standardized marine environmental variables and second HCA with the socioeconomic PCA components, to identify homogenous marine environmental and socioeconomic classes, respectively. We used Euclidean distance and Ward's method as agglomerative hierarchical techniques (Ward, 1963). Third, we conducted ANOVA and Kruskal-Wallis tests to test for differences in the considered variables (see Table S1 and S2 in Appendix A) among the multiple classes obtained by the marine environmental and socioeconomic HCAs. When the ANOVA and Kruskal-Wallis tests were significant (p-value < 0.05), we used *post hoc* pairwise comparisons t-tests and Dunn's multiple comparisons tests, respectively, to assess the differences between classes. The Shapiro-Wilk test was initially used to check for normality for all the marine environmental and socioeconomic variables used.

Finally, we performed a Chi-squared contingency table analysis to explore the level of association between the identified marine environmental and socioeconomic classes and, thus, to identify the CMSESs. To graphically visualize the differences among CMSESs, we conducted a non-metric multidimensional scaling (nMDS) based on Euclidean similarity, taking its stress value as an indicator of the goodness of representation. Radar charts were used to represent the influence of the socioeconomic and marine environmental variables on each CMSES. We used R software (R Core Team, 2015) to conduct the statistical analyses.

3. Results

3.1. Marine environmental classifications

Through the HCA, we identified five marine environmental classes (MECs) (Fig. 3a). Whereas the municipalities of MEC2 were characterized by the highest concentrations of nitrate and phosphate ($2.02\,\text{mol/m}^3$ and $0.18\,\text{mol/m}^3$, respectively) (Table 1), MEC3 was characterized by the highest values of calcite ($3.47\text{e-}4\,\text{mol/m}^3$), minimum chlorophyll *a* ($0.68\,\text{mg/m}^3$), and mean chlorophyll *a* ($1.99\,\text{mg/m}^3$) (Table 1). The municipalities in MEC5 were characterized by the highest values of maximum SST (25.55 °C), mean SST (19.18 °C), SST range (11.21 °C) and salinity (37.10 PSS) (Table 1). This class also had the lowest values of the remaining marine environmental variables, i.e., calcite, mean chlorophyll *a*, minimum chlorophyll *a*, nitrate, and phosphate. Finally, MEC1 and MEC4, which were geographically located between MEC2 and MEC5 (Fig. 3a), had intermediate values of all marine environmental variables. The Kruskal-Wallis tests showed significant differences in all marine environmental variables among these classes (Table 1).

3.2. Socioeconomic classifications

The first eight components of the PCA presented eigenvalues higher than 1 (i.e., Kaiser criteria) and explained 78% of the variance in the socioeconomic data (see Table S3 in Appendix B). The first socioeconomic component, PCA1 (13% of the variance), represented by its positive scores those municipalities with high population densities and whose populations have university degrees and work in the tertiary sector. In contrast, the negative scores of PCA1 represented those municipalities with high rates of illiterate people and with meadows. PCA2 (12%) had a gradient based on age, with those municipalities representing people younger than 25 with positive scores and those with people older than 65 with negative scores. PCA3 (11%) was associated with the land uses of rivers and lakes, non-productive surfaces, and fallows and with people mainly employed in the primary sector. PCA4 (11%) was associated with high rates of protected surfaces, both terrestrial and marine. PCA5 (10%) encompassed those variables representing the fishing activity (catches, fishing vessels, and fishers). PCA6 (9%) was associated with high annual income and with a population employed in the secondary sector. PCA7 (7%) represented those municipalities with high rates of unemployment and non-agricultural surfaces. Finally, PCA8 (6%) was associated with tourism activity.

By using these eight PCA components in the HCA, we identified five socioeconomic classes (SECs) (Fig. 3b; Table 2). The municipalities within SEC1 and SEC2 had the highest population densities (235.09 and 757.48 inhabitant km^{-2}, respectively), but they differed in education level. Whereas municipalities within SEC1 had the highest percentage of illiterate people (3.67%), the municipalities within SEC2 had the highest rate of people with university-level education (14.04%). In addition, the municipalities within SEC2 were also characterized by the lowest percentage of people employed in the primary sector (2.30%). In contrast, SEC1 and SEC5 represented those municipalities with the highest percentage of the population employed in the primary sector (12.89% and 32.21%, respectively). SEC1 and SEC5 had other commonalities, as both classes represented those municipalities with the highest percentage of fallow land use (13.77% and 14.42%, respectively) (Table 2). SEC1 also had the highest percentage of surface with non-productive and non-agricultural land uses (6.67%, 15.06%, respectively) (Table 2).

SEC3 was represented by those municipalities with the highest rates of terrestrial and marine protected areas (53.07% and 9.02%, respectively) (Table 2). Finally, SEC4 was characterized by distinctive demographic, economic, and land-use variables. Demographically, the municipalities within SEC4 had the highest percentage of people younger than 25 years old (29.31%). Economically, SEC4 had the highest annual income (1863.11€) and the highest percentage of people employed in the secondary sector (15.45%). However, this class also had the highest rate of unemployment (12.35%). Regarding land uses, SEC4 was characterized the highest percentage of surface belonging to mountains (57.23%) and rivers and lakes (2.67%) (Table 2). Regarding the variables for fishing activity, we did not find differences among the SECs, although SEC4 and SEC5 showed no activity (Table 2).

3.3. Characterization of the CMSESs

We found a significant association between the socioeconomic and marine environmental classes ($\chi^2 = 47.27; p < 0.001$), which resulted in twelve CMSES (Figs. 4 and 5). However, MEC2 and MEC4 were only associated by one SEC, i.e., SEC3 and SEC2, comprising CMSES2 and CMSES5, respectively, and the remaining three marine environmental classes were associated with different socioeconomic classes. CMSES2 was geographically located in the western region of the Andalusian coastline (Fig. 5b) and was characterized by high levels of nitrates and phosphates (i.e., MEC2) and a high representation of terrestrial and marine protected areas (i.e., SEC3) (Fig. 6b). CMSES5 was located in the central area of the Malaga coastline (Fig. 5b) and was mainly characterized by municipalities with high population densities and a high rate of people with university-level education (SEC2; Table 2). Environmentally, CMSES5 had intermediate values of all marine environmental variables that comprised the marine environmental class of MEC4 (Fig. 6e).

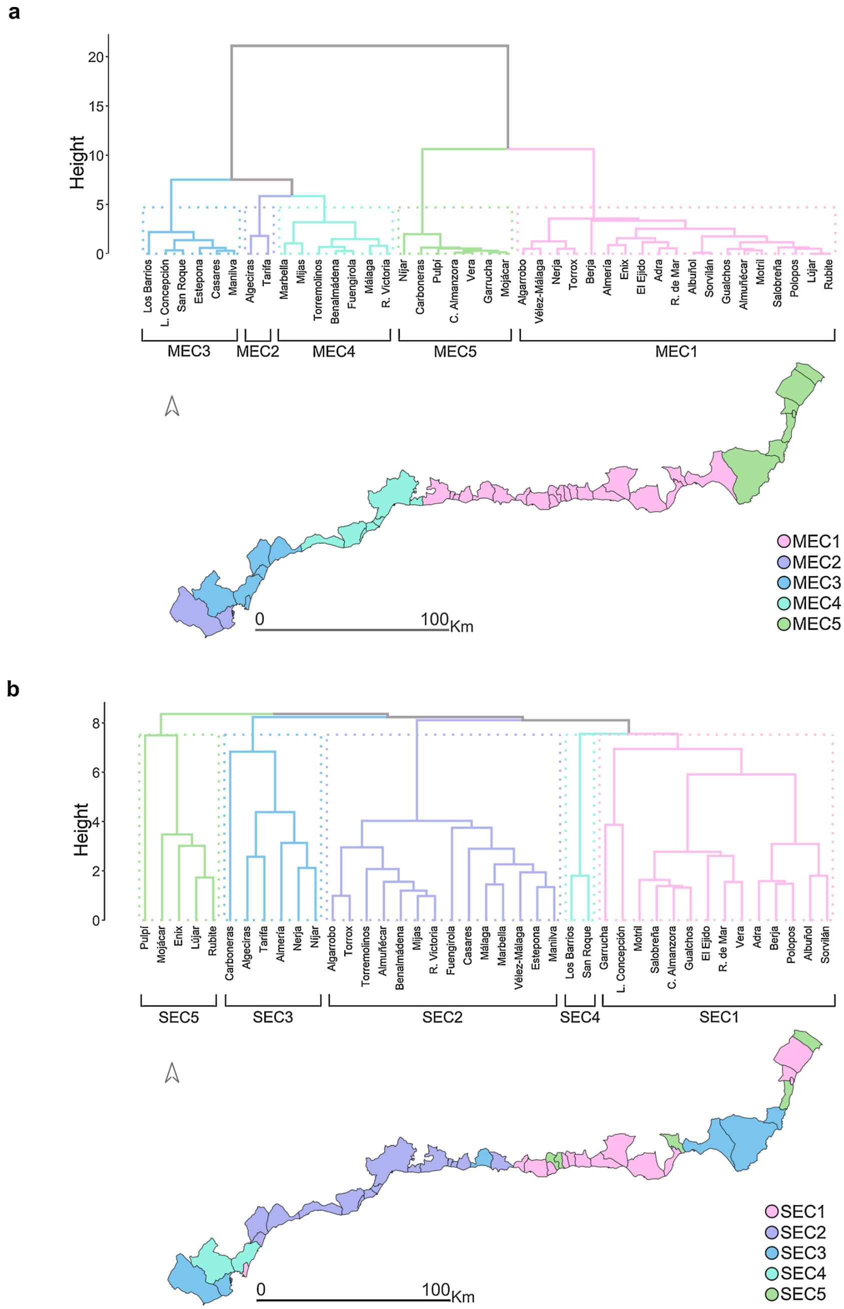

Fig. 3. Dendrogram and map with the municipalities included in each (a) marine environmental class (MEC) and (b) socioeconomic class (SEC).

The other marine environmental class that had intermediate values for all variables (MEC1) was associated with four different socioeconomic classes (SEC1, SEC2, SEC3, and SEC5), comprising CMSES1, CMSES9, CMSES10, and CMSES11, respectively (Fig. 4). All of these CMSESs were characterized by the same marine environmental variables, but they actually differed in socioeconomic characteristics and thus represented different coastal areas of Malaga, Granada, and Almeria (Fig. 5b). Whereas CMSES9 and CMSES10 were located in the eastern part of Malaga, CMSES1 and CMSES 11 were distributed throughout Granada and in western Almeria. In addition, it is remarkable that while CMSES1 was broadly spread throughout these provinces, CMSES11 appeared in very few areas (Fig. 5b). This difference relied on the socioeconomic differences: whereas CMSES11 represented municipalities with a high rate of employment in the primary sector (Fig. 6k), CMSES1 represented those municipalities with a high percentage of land surface with non-productive and non-agricultural land uses (Fig. 6a). The differences between CMSES9 and CMSES10 in eastern Malaga also depended on socioeconomic aspects. Whereas

Table 1
Mean values of the marine environmental variables in each marine environmental class (MEC) and X^2 statistic for the significant differences among the MECs. The MECs sharing superscript letters (a, b, or c) do not differ (Dunn's multiple comparison tests after Bonferroni correction). The bold values point to the MEC with the highest mean value for each variable. ** $p < 0.01$.

Variables	MEC1	MEC2	MEC3	MEC4	MEC5	X^2
Mean calcite (mol/m^3)	2.86E-04^{a}	2.98E-04^{a,b}	**3.47E-04**^{a}	2.95E-04^{a}	1.28E-04^{b}	21.58**
Mean chlorophyll a (mg/m^3)	0.87^{a,b}	0.63^{a,b}	**1.99**^{c}	1.19^{a,c}	0.35^{b}	34.31**
Minimum chlorophyll a (mg/m^3)	0.29^{a}	0.35^{a,b}	**0.68**^{b}	0.58^{b}	0.16^{a}	34.50**
Mean nitrate (mol/m^3)	1.42^{a,b}	**2.02**^{a,c}	1.96^{c}	1.75^{a,c}	1.15^{b}	35.16**
Mean salinity (PSS)	36.92^{a,b}	36.34^{a,c}	36.47^{c}	36.77^{a,c}	**37.10**^{b}	35.16**
Maximum SST (°C)	24.38^{a,b}	21.79^{a,c}	22.02^{c}	23.19^{a,c}	**25.55**^{b}	35.42**
Mean SST (°C)	18.67^{a,b}	18.18^{a,c}	17.76^{c}	18.35^{a,c}	**19.18**^{b}	36.34**
Range SST (°C)	9.72^{a,b}	6.39^{a,c}	7.19^{c}	8.32^{a,c}	**11.21**^{b}	35.52**
Mean phosphate (mol/m^3)	0.14^{a,b}	**0.18**^{a,c}	0.17^{c}	0.16^{a,c}	0.11^{b}	35.47**

Table 2
Mean values of the socioeconomic variables in each socioeconomic class (SEC), *F-value*, and X^2 statistic for the significant differences among the socioeconomic classes. The SECs sharing superscript letters (a, b or c) do not differ (pairwise comparison t − tests or Dunn's multiple comparison tests after Bonferroni correction). The bold values point to the SEC with the highest mean value for each variable. * $p < 0.05$, ** $p < 0.01$.

Type	Variables	SEC1	SEC2	SEC3	SEC4	SEC5	*F*	X^2
Demographic	Population density (Ln)	5.46^{a}	**6.63**^{a}	5.21^{a,b}	4.78^{a,b}	3.22^{b}	6.11**	
	Illiterate people (%)	**3.67**^{a}	2.06^{a,b}	2.68^{a,b}	2.15^{a,b}	0.37^{b}		15.57**
	People with a university degree (%)	7.51^{a}	**14.04**^{b}	11.17^{a,b}	9.16^{a,b}	7.78^{b}	3.14*	
	People younger than 25 (%)	28.19^{a}	26.06^{a,b}	27.22^{a,b}	**29.31**^{a,b}	17.18^{b}		13.47**
	People older than 65 (%)	14.43	16.61	15.12	12.88	23.14		9.81*
Economic	People employed in primary sector (%)	12.89^{a}	2.30^{b}	6.41^{a,b}	0.57^{a,b}	**32.21**^{a}		16.44**
	People employed in secondary sector (%)	2.79^{a}	3.66^{a,b}	4.31^{a,b}	**15.45**^{b}	4.30^{a,b}		9.77*
	People employed in tertiary sector (%)	15.83	22.43	26.11	22.51	20.13	2.37	
	People unemployed (%)	9.87^{a}	9.48^{a}	10.42^{a}	**12.35**^{a}	5.80^{b}	7.24**	
	Annual income per inhabitant (Ln)	6.92^{a}	7.32^{b}	7.01^{a,b}	**7.53**^{b}	7.18^{a,b}	6.11**	
	Tourist accommodations (N/km)	0.21	0.94	0.26	0.08	0.12		9.74*
Land use	Mountains (%)	11.18^{a}	0.05^{b}	24.72^{a}	**57.23**^{a}	17.36^{a}		28.22**
	Meadows (%)	22.24	15.99	9.97	16.50	29.99		7.61
	Non-productive (%)	**6.67**^{a}	0.33^{b}	3.78^{a,b}	3.98^{a,b}	4.24^{a,b}		24.76**
	Non-agricultural (%)	**15.06**^{a}	0.89^{b}	8.01^{a,b}	14.14^{a,b}	5.90^{a,b}		23.32**
	Rivers and lakes (%)	1.76^{a}	0.01^{b}	1.28^{a,b}	**2.67**^{a}	2.39^{a}		28.15**
	Crops (%)	21.02	16.13	7.72	3.23	12.48		6.73
	Fallow (%)	13.77^{a}	0.96^{b}	0.36^{b,c}	0.60^{a,b}	**14.42**^{a,c}		24.86**
	Livestock (individual/Ha)	0.06	0.07	0.10	0.16	0.23		2.84
Fishing activity	Catches (N/km)	3.92	4.00	6.78	0.00	0.00		5.032
	Fishing vessels (N/km)	1.59	0.89	0.51	0.00	0.00		4.53
	Fishers (%)	0.13	0.08	0.89	0.00	0.00		7.02
Protection	Land protected area (%)	1.08^{a}	1.54^{a}	**53.08**^{b}	46.31^{a,b}	0.00^{a}		26.07**
	Marine protected area (%)	0.00^{a}	0.11^{a}	**9.02**^{b}	0.00^{a}	0.00^{a}		35.11**

CMSES9 had similar characteristics to CMSES5 in terms of a high population density and a high percentage of people with university-level education (Fig. 6i and e), CMSES10 had a high percentage of both terrestrial and marine protected areas (Fig. 6j).

The marine environmental class of MEC3, represented by the eastern region of Cadiz and western Malaga, was characterized by high levels of primary production (i.e., chlorophyll *a*). MEC3 was associated with three socioeconomic classes (SEC1, SEC2, and SEC4) representing three social-ecological systems: CMSES12, CMSES4, and CMSES3, respectively. Each of these social-ecological systems was distinctively located in different regions: CMSES12 represented the unique municipality in Cadiz bordering Gibraltar (a British overseas territory), CMSES3 represented other municipalities in Cadiz, and CMSES4 represented municipalities in Malaga (Fig. 5b). The administrative differences in the municipalities entailed different socioeconomic characteristics (Fig. 6). Whereas CMSES3 was characterized by the highest

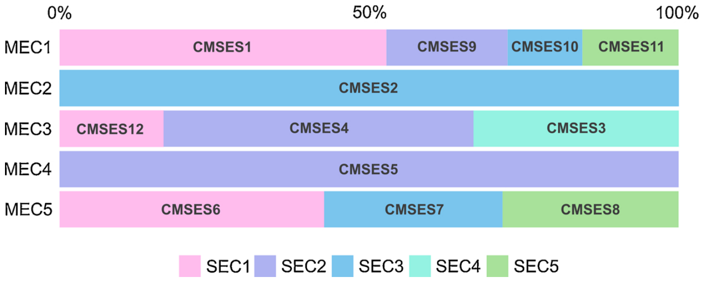

Fig. 4. Bar diagram representing the associations among the marine environmental (MEC) and socioeconomic (SEC) classes and the consequent CMSESs. ($\chi2 = 47.27$; $p < 0.001$).

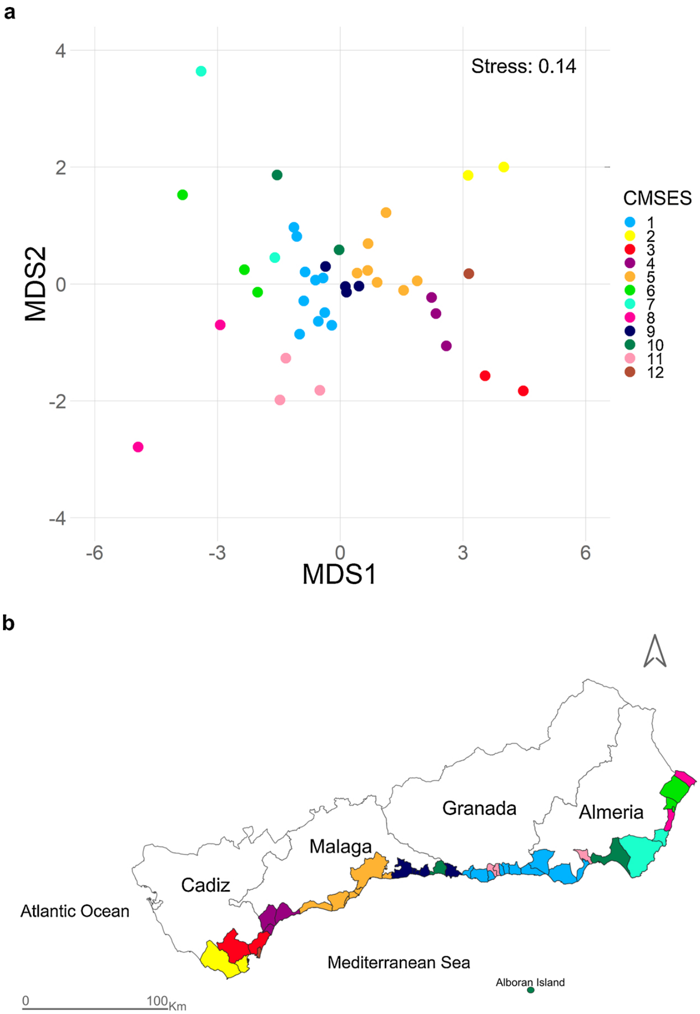

Fig. 5. (a) Two-dimensional nMDS (nonmetric multidimensional scaling) of the coastal marine social-ecological systems (CMSESs) based on socioeconomic and marine environmental characteristics. (b) Map with the geographic location of each CMSES.

rate of young people and people working in the secondary sector (Fig. 6c), CMSES 4 had a high population density and percentage of people university-level education (Fig. 6d). In contrast, CMSES12 was characterized by a high rate of illiterate people (Fig. 6l).

The eastern region of the Andalusian coastline was environmentally characterized by the highest values of SST and salinity and the lowest productivity, which were characteristic features of the marine environmental class of MEC5. Despite the environmental similarities in the region, the socioeconomic differences entailed multiple CMSESs. MEC5 was associated with the socioeconomic classes of SEC1, SEC3, and SEC5, representing CMSES6, CMSES7, and CMSES8 (Fig. 4). Whereas CMSES6 had a high percentage of illiterate people and a high percentage of land surface with non-productive and non-agricultural land uses (Fig. 6f), CMSES8 was characterized by a high percentage of people working in the primary sector and a high percentage of fallow surface (Fig. 6h). Both CMSES6 and CMSES8 had a small percentage of terrestrial and marine protected areas. In contrast, CMSES7 was characterized by a high percentage of terrestrial and marine protected areas (Fig. 6g).

4. Discussion and conclusions

Through the application of a methodological framework used formerly in terrestrial systems (Martín-López et al., 2017), this study spatially identified twelve CMSESs. Each CMSES represented a homogenous, although geographically continuous or discontinuous, area of varying sizes characterized by similar associations between the socioeconomic and marine environmental characteristics. Therefore, our study provides a methodological framework to characterize and spatially locate the social-ecological systems in coastal marine systems. Far from trivial, accurate spatial localization of social-ecological systems is one of the main limitations on using the framework of social-ecological systems in marine management (de Andrés et al., 2017).

Despite the capacity of the suggested methodological approach to identify CMSESs, we should note some of its limitations. First, future studies seeking to improve integrated management will benefit from taking into account biological information such as species richness, abundance, biomass or functional biodiversity (Micheli and Halpern, 2005). Because local biodiversity results from numerous factors, including local environmental conditions, we believe that the identified

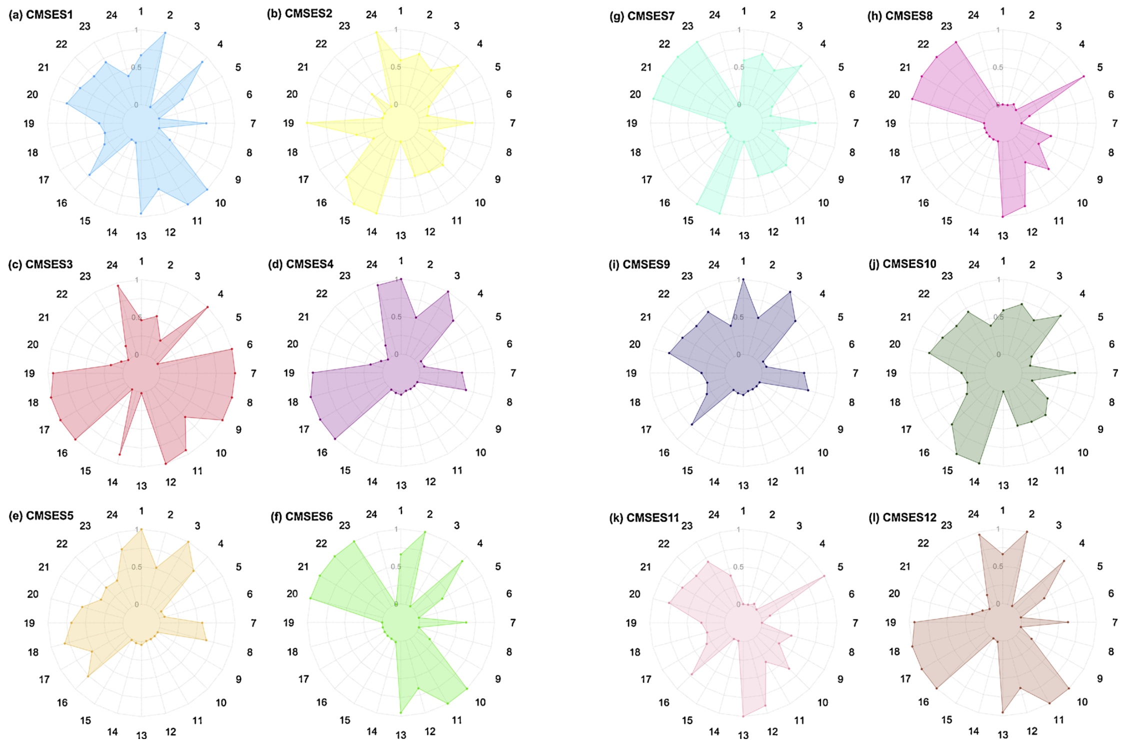

Fig. 6. Socioeconomic and marine environmental variables that characterize the CMSESs from (a) to (l). The peripheral numbers from 1 to 24 are codes for the socioeconomic and marine environmental variables: (1) population density, (2) illiteracy, (3) people with a higher education, (4) people younger than 25, (5) people employed in the primary sector, (6) people employed in the secondary sector, (7) people who are unemployed, (8) annual income per inhabitant, (9) mountains, (10) non-productive, (11) non-agricultural, (12) river and lakes, (13) fallow, (14) land protected area, (15) marine protected area, (16) mean calcite, (17) mean chlorophyll *a*, (18) minimum chlorophyll *a*, (19) mean nitrate (20) mean salinity, (21) maximum SST, (22) mean SST, (23) SST range, and (24) mean phosphate.

CMSESs might also differ in biodiversity. For example, Bermejo et al. (2015) identified three subregions of macrophyte diversity in the western Mediterranean that were closely related to marine environmental variables. The CMSESs identified in this study perfectly fit within the biogeographical regions described by Bermejo et al. (2015). The CMSESs that comprised the marine environmental classes of MEC1, MEC2, and MEC3 (i.e., CMSES1-4 and CMSES 9–12; Fig. 4) matched the biogeographic region of eastern Alboran. CMSES5 matched the biogeographic region of central Alboran. The CMSESs encompassing the marine environmental class of MEC5 (i.e., CMSES 6–8; Fig. 4) matched the biogeographic region of western Alboran. The environmental overlap between both studies evidences differences in the marine macrophyte composition across the identified CMSESs.

Second, the use of municipal statistics does not account for the different governance that occurs due to different policies at the province level. However, the resulting CMSESs showed that the association between marine environmental and socioeconomic characteristics can be the result of government processes at the provincial scale because the identified CMSESs perfectly fit within the borders of the provinces of Cadiz and Malaga and Malaga and Granada. Despite the differences in the CMSESs between provinces and within each province, the Andalusian Strategy for Integrated Coastal Zone Management, resulting from the application of the EU Recommendation on Integrated Coastal Zone Management Marine (2002/413/EC), provides the same legal guidelines for all of Andalusia. This research shows that different CMSESs would benefit from considering their marine environmental and socioeconomic similarities and differences in the policies and management of the coastal marine zones.

We identified twelve CMSESs that conformed to the intermediate areas between provinces and municipalities, e.g., the CMSESs reflected important differences and similarities within and between provinces and municipalities. The specific marine environmental and socioeconomic factors behind the similarities and differences between CMSESs are essential to designing and using management measures and to policy-making decisions. For example, as CMSES2, CMSES3, and CMSES12 were situated in the province of Cadiz, their management relies on the ICZM and the recently approved 'Program for the Coastal Management of the Cadiz province' (July 24th, 2018). However, these CMSESs required distinctive management actions based on their social-ecological characteristics.

CMSES3 and CMSES12 shared the same marine environmental characteristics, whilst CMSES2 differed from them by both marine environmental and socioeconomic characteristics. The marine environmental differences can be explained by the fact that CMSES2 was located in the Strait of Gibraltar, where the Atlantic Ocean connects to the Mediterranean Sea (Coll et al., 2010), and the mix of both waterbodies leads to unique biophysical characteristics, i.e., high concentration of nutrients, low SST, and low salinity (Minas et al., 1991). In contrast, CMSES3 and CMSES12, together with CMSES4 in western Malaga, were environmentally characterized by high productivity and a low SST, which can be explained by a quasi-permanent upwelling region in this area (Navarro et al., 2011).

Socioeconomically, CMSES3 and CMSES12 face different challenges. For example, management actions directed to develop education programmes may result in increased awareness about the importance of the coast and the marine systems in CMSES12, which has a low percentage of protected areas and the highest percentage of illiterate people. In contrast, a potential future challenge for CMSES3 might be dealing with human pressure, as this is the CMSES with the highest percentage of young people. These examples show how the classification of CMSESs can support the design of management measures and policies that effectively target the social-ecological realities at local and regional scales.

Furthermore, our results also showed that the design of management programmes at the province level might be counterproductive because some CMSESs are located across borders or because of the diversity of CMSESs within a province. As an illustration of CMSESs located across provinces, we found four CMSESs that overlap borders: CMSES1 and CMSES11 that comprise municipalities in Granada and Almeria, CMSES9 in Malaga and Granada, and CMSES10 in Malaga and Almeria. These four CMSESs shared the same marine environmental characteristics, as they were influenced by the northwestern upwelling, but they clearly differed in their socioeconomic characteristics (i.e., population density, land uses, and education level). Therefore, management measures and policies should target their challenges according to these differences. For example, the highest population density within CMSES9 suggests that management and policies should target particular anthropogenic pressures, such as urban sprawl or an increase in resource consumption. In contrast, the challenge for CMSES11 is to manage the increasing population employed in the agricultural sector. In fact, the expansion of greenhouses and intensive agriculture in this CMSES has led to a loss of ecosystem services such as hydrological regulation, water purification, and aesthetic beauty (Garcia-Llorente et al., 2015; Requena-Mullor et al., 2018).

Almeria, with six CMSESs, was a perfect example of the high diversity of CMSESs within a single province: CMSES1, CMSES6, CMSES7, CMSES8, CMSES10, and CMSES11. The marine environmental characteristics divide the coastline of Almeria into a western region (CMSES1, CMSES10, and CMSES11) and an eastern region with warmer, salty, and unproductive water (CMSES6, CMSES7, and CMSES8). These characteristics were associated with the oceanographic variations of the Mediterranean Sea that show a gradual increase in SST and a gradual decrease in chlorophyll *a* with increasing distance from the Gibraltar Strait. In addition to marine environmental differences, socioeconomic differences highlight that specific management actions according to marine environmental and socioeconomic characteristics should be addressed. For instance, the high percentage of illiterate people in CMSES6, together with the low primary productivity of this area, suggests that management measures and policies should focus on environmental education oriented to promote sustainable fisheries. By comparison, the management challenge in CMSES7 and CMSES10 with a high percentage of terrestrial and marine protected areas is to increase and improve the surveillance of these protected areas to minimize poaching while promoting the development of new economic sectors with respect to nature, e.g., ecotourism.

The CMSESs identified in our study represent distinct associations between socioeconomic and marine environmental characteristics. Our results suggest new directions for coastal planning and management, which should focus on the specific characteristics and conservation challenges of each CMSES. As in other parts of the world, these conservation challenges range from reducing local human pressures, such as pollution derived from intensive agriculture (e.g., CMSES11) or urbanization of the coastline (e.g., CMSES9), to counteracting globally induced impacts such as climate change and overexploitation of fisheries (Anticamara et al., 2011; Broderick, 2015; de Andrés et al., 2017).

The Andalusian Regional Ministry of Environment and Territory has designed an integrated coastal zone management strategy that takes into account both the socioeconomic development and ecological fragility of the coastal system in the management of coastal and marine systems (Council of Europe, 2000). However, the differences between CMSESs were not considered. Although there is substantial progress in the integrated management of coastal marine areas in Andalusia, there are still important shortcomings (Barragán, 2003). First, the current management of the marine coastal areas in Andalusia seeks to address general problems, such as pollution, overfishing, biodiversity loss, reduction of economic possibilities, and loss of cultural and natural heritage, without appropriate consideration of CMSESs (Barragán et al., 2008). Second, the large number of institutions with coastal jurisdiction (e.g., Regional Ministry of Environment and Territory, the City Council, and the Spanish Ministry of Agriculture and Fisheries, Food and Environment) challenges coordination and jeopardizes an integrated management system that considers the distinctiveness of CMSESs (Barragán et al., 2008; Suárez de Vivero and Rodríguez Mateos, 2005). In this regard, our study provides a methodological framework that can facilitate the coordination between multiple institutions and integrate information from different sources.

The precise characterization of coastal regions in terms of socioeconomic and environmental variables can contribute to prioritizing the differential integrated management measures in each CMSES. Based on our results, distinctive management actions were identified according to the social-ecological characteristics of the CMSESs, such as environmental education programmes, the control of agro-chemical consumption in intensive agriculture and the promotion of organic agriculture, or formal rules and norms that counteract current urban sprawl. In addition, the accurate spatial localization of CMSESs contributes to identifying the specific management actions required for each area and the stakeholders that should be involved. The methodological approach developed in this research effectively identified and characterized the social-ecological associations that occur in coastal marine systems. Our approach can therefore be a useful tool for designing more efficient management actions and policies that can be implemented at more relevant scales in marine coastal areas.

Acknowledgements

Financial support was provided by the Project MARINERES, CGL2013-49122-C3-1-R of the Spanish Ministry of Economy and Competitiveness. We thank Dr. David Peterson and two anonymous reviewers for their constructive comments, which helped improve the quality of our manuscript.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2018.11.003.

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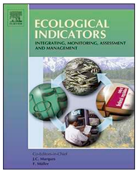
Ecological Indicators 109 (2020) 105786

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Original Articles

Alpha and beta diversity across coastal marine social-ecological systems: Implications for conservation

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ARTICLE INFO

Keywords:
Andalusia
Coastal management
Littoral fish
Marine biodiversity
Mediterranean Sea

ABSTRACT

Cumulative anthropogenic activities in coastal regions are a major threat to their marine biodiversity. The consideration of coastal marine areas as social-ecological systems (CMSESs) can be useful for marine biodiversity conservation. This integrative approach incorporates social information that can link anthropogenic activities to marine biodiversity, providing opportunities for improving conservation policies tailored to the specific reality of the CMSESs. Here, we assessed the beta and alpha diversity of the shallow littoral fish communities present in the Andalusian CMSESs and explored how they relate to socioeconomic and marine environmental variables. We used underwater visual surveys to estimate the fish abundance data needed to calculate the alpha and beta diversity of the fish species. We quantified the species and functional beta diversity using abundance-based data. We also quantified species richness index as indicators of species alpha diversity, and functional evenness as indicators of functional alpha diversity. We found that the association of marine environmental and socioeconomic variables with biodiversity varied with CMSES. Empirical inclusion of biodiversity in social-ecological systems research of marine and coastal areas can provide insights on human-nature dynamics. This can contribute to design more effective marine biodiversity conservation programs that consider both the socioeconomic and marine environmental characteristics of each CMSES.

1. Introduction

Oceans and seas have lost almost one percent of marine biodiversity per year in the last forty years (WWF, 2016). It seems an excessively high rate for a system that contributes so much to human quality of life through the provision of ecosystem services (Agardy et al., 2005; Liquete et al., 2013a) and that is essential for the social-ecological resilience (Beaumont et al., 2007; Martínez et al., 2007; Liquete et al., 2013b; Neumann et al., 2015). There is strong evidence that the cumulative and synergistic effects of multiple anthropogenic pressures including fisheries overexploitation, climate change, ocean acidification, pollution, and habitat destruction are jeopardizing the future of marine biodiversity (Halpern et al., 2008; Rocha et al., 2018). Not surprisingly, marine biodiversity is a conservation priority under numerous international agreements such as the Sustainable Development Goals (i.e., SDG 14) or the Convention on Biological Diversity Strategic Plan for Biodiversity (i.e., Aichi Target 11). Likewise, the scientific community is also addressing the conservation challenges of marine biodiversity by creating global research networks (Bennett, 2018) such as the Future Earth research cluster and knowledge-action-network on coasts (Future Earth Coasts, 2018; Future Earth Oceans, 2018) or the Taskforce on Ocean Governance of the Earth Systems Governance project (Earth System Governance, 2018). Along with these initiatives, UNESCO has announced that 2021–2030 will be the Decade of Ocean Science for Sustainable Development (UNESCO, 2018; Visbeck, 2018).

Scientifically, these initiatives stress the need for interdisciplinary research of marine biodiversity to ensure the sustainable use of the ocean. The social-ecological approach deepens in the study of human-nature dynamics, and it is particularly relevant for understanding how humans impact natural systems (Glaser et al., 2012). The social-ecological approach is well suited to provide insights about human-nature dynamics and, therefore, to contribute to reveal the management practices needed to preserve marine biodiversity (Christie et al., 2017; Bennett, 2018). Although the number of studies evaluating social-

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https://doi.org/10.1016/j.ecolind.2019.105786
Received 2 February 2019; Received in revised form 25 September 2019; Accepted 30 September 2019

ecological interactions in coastal and marine systems has increased substantially in the last decade (e.g., Cinner et al., 2009; Álvarez-Romero et al., 2011; Ban et al., 2013), less than 15% of these studies included biodiversity aspects when analyzing the social-ecological dynamics of coastal and marine systems (Rissman and Gillon, 2016). Therefore, the need for biodiversity assessments in coastal and marine social-ecological systems (CMSESs) looms large.

The Mediterranean Sea is one of the most diverse and threatened marine biodiversity hotspots of the world (Myers et al., 2000; Coll et al., 2010, 2012). It hosts more than 600 fish species, which are highly threatened by direct and indirect anthropogenic impacts such as overfishing, marine pollution and fish species invasions (Reynolds et al., 2005; Coll et al., 2012). Recent studies on the western coast of the Mediterranean Sea evidence that coastal areas differ in socioeconomic and marine environmental characteristics (Lazzari et al., 2019). How these characteristics interact with biodiversity is yet unknown.

Our study aims to evidence the relationships between the alpha and beta biodiversity of littoral fish communities of the Andalusian coast, and the socioeconomic and marine environmental characteristics. Knowledge on such links may contribute to design management measures that effectively targeted the specific relationships between the environmental, socioeconomic, and biological characteristics of each CMSESs.

2. Study area

Our study covered part of the coastlines of Malaga, Granada, and Almeria provinces for an approximate total length of 300 km of the Andalusian region, in southern Spain (Fig. 1). The study area included six CMSESs. Each CMSES represents a homogenous area of varying size characterized by similar associations between socioeconomic and marine environmental variables (Lazzari et al., 2019). Despite their homogeneity, a single CMSES may occupy discontinuous geographic areas (Fig. 1).

We sampled six CMSESs (i.e., CMSES5, CMSES9, CMSES10, CMSES1, CMSES11, and CMSES7, geographically ordered from west to east), which spread over several provinces (Fig. 1). In Malaga, we sampled CMSES5 and CMSES9. Both CMSESs share the same socioeconomic characteristics, presenting high population density and a high percentage of people with university-level education (Fig. 2). By contrast, the CMSES1 and CMSES11, which spread over the provinces of Granada and Almeria, have the lowest rate of people with university-level education. In Almeria, CMSES10 and CMSES7, together with CMSES1, have the lowest annual income per inhabitant (Fig. 2). Environmentally, CMSES5 and CMSES7 have the lowest and highest values of sea surface temperature and salinity, respectively, while the remaining CMSES9, CMSES10, CMSES1, and CMSES11 have intermediate values (Fig. 2). For more details, see Table S1 and Lazzari et al. (2019).

3. Data collection and analyses

3.1. Data sampling

We focused our study on the fish community inhabiting littoral rocky reefs of Andalusia. Fish are the most diverse vertebrate group, play an essential ecological role, and are highly impacted by anthropogenic activities such as overfishing (Reynolds et al., 2005). Following the standard Reef Life Survey (RLS) protocol, we collected fish abundance data from 53 sites in the six CMSESs of the Andalusian coast, during summer 2014–2016. We did a maximum of two transects per site, parallels to the coastline, and each site was distanced from others by at least 200 m. We sampled 5 sites in CMSES5 and CMSES9, 6 sites in CMSES10, 11 sites in CMSES1, 8 sites in CMSES11 and 18 sites in CMSES7. RLS is a citizen science program that trains divers to collect biodiversity information using a standardized underwater visual census technique (Edgar and Stuart-Smith, 2014). Two RLS divers (NL and JAS-F) obtained 95% of the data used in this study. RLS divers count the

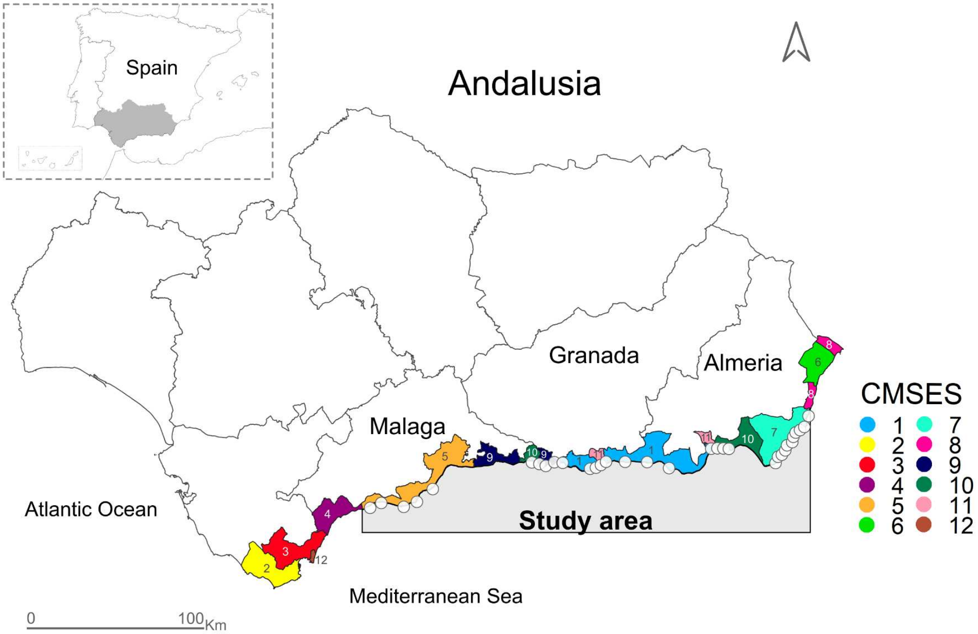
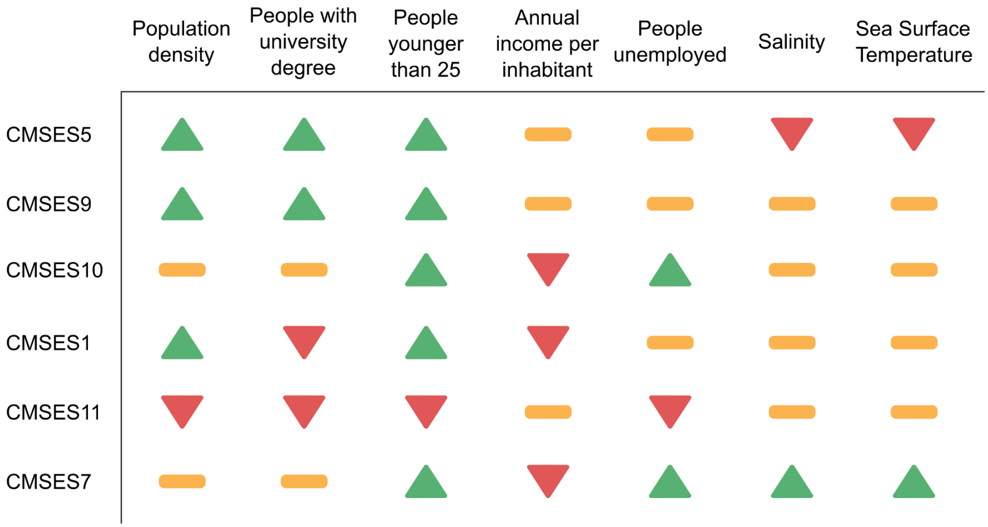


Fig. 1. Map of the study area in the Mediterranean coast of Andalusia (grey box). The map shows the geographic location of the biological sampling points (white dots) and the coastal marine social-ecological systems (CMSES) to which they belong. We sampled six out of the 12 CMSESs in the region because they were the CMSESs with the highest percentage of hard substrate.



	Population density	People with university degree	People younger than 25	Annual income per inhabitant	People unemployed	Salinity	Sea Surface Temperature
CMSES5	▲	▲	▲	▬	▬	▼	▼
CMSES9	▲	▲	▲	▬	▬	▬	▬
CMSES10	▬	▬	▲	▼	▲	▬	▬
CMSES1	▲	▼	▲	▼	▬	▬	▬
CMSES11	▼	▼	▼	▬	▼	▬	▬
CMSES7	▬	▬	▲	▼	▲	▲	▲

Fig. 2. The seven socioeconomic and marine environmental variables contributing the most (> 70%) to the characterization of CMSESs. Green up arrows, yellow lines, and red down arrows represent high, medium, and low values of each variable, respectively. To make the results comparative and descriptive, these classes were based on a relative classification of the variables, limited by their 33rd and 66th percentiles. CMSESs geographically ordered from west to east. For more details, see Table S1 and Lazzari et al. (2019).

abundance of each fish species sighted along a 50-m long, 5-m wide belt transect (total surface sampled = 250 m^2), obtaining suitable data for the quantification of several biodiversity measures (Edgar and Stuart-Smith, 2014; Edgar et al., 2016, 2017). Full details of the standardized RLS survey procedures are available in an online methods manual (https://reeflifesurvey.com/wp-content/uploads/2015/07/NEW-Methods-Manual_150815.pdf).

3.2. Data analysis

3.2.1. Beta and alpha diversity

Species and functional beta diversity refer to the difference in species and functional traits between sites, respectively (Anderson et al., 2011). For fish species diversity, we generated a matrix of species by sites. To evaluate functional diversity of marine fish communities, we used 18 levels of five relevant functional traits (i.e. maximum length, trophic group, water column position, habitat complexity, and gregariousness; see Table 1), which were were obtained from FishBase (www.fishbase.org; Froese and Pauly, 2000) and the database used in Stuart-Smith et al. (2013). These traits provide information on key physiological, behavioral, and environmental aspects (Stuart-Smith et al., 2013; Mouillot et al., 2014). Then, we created a matrix of functional traits' levels by sites. The measurement of each species and each trait in a site was calculated as the average of its abundance for all transects in this site. Table S2 shows how specific functional traits were assigned to each fish species. We used the log (x + 1) transformed abundance data of species and functional traits, to calculate an abundance-based beta diversity indicator based on Bray-Curtis dissimilarity, which is less dependent on sample size than incidence-based beta diversity (Socolar et al., 2016). We used the *beta.pair.abund* function of the 'betapart' R package (Baselga, 2017) to calculate the abundance-based beta diversity indicator as the total pairwise dissimilarities of fish species and functional traits between sites (Baselga, 2017).

To estimate species alpha diversity, we used the indicator of species richness (i.e., the average of the total number of species of each transect in a site). We used the *diversity* function of the 'vegan' R package (Oksanen et al., 2019) to calculate the species richness. To quantify functional alpha diversity, we used functional evenness, which is defined as the uniform distribution of abundance in the functional trait space (Mason et al., 2005; Villéger et al., 2008). We selected this functional metric because it includes more than one functional trait and it is weighted by the relative abundances of species (Botta-Dukát, 2005; Villéger et al., 2008; Laliberté and Legendre, 2010). To calculate the functional evenness, we used the *dbFD* function of the 'FD' R package (Laliberté and Legendre, 2010).

3.2.2. Socioeconomic and marine environmental variables

We used socioeconomic and marine environmental variables that were relevant in the characterization of CMSESs in Andalusia (Lazzari et al., 2019). We considered five socioeconomic aspects in our analysis: demography, economy, coastal land uses, sea use, and environmental protection. We obtained 24 socioeconomic variables, which were categorized in those five socioeconomic aspects. Variables were obtained from the Andalusian Multi-Territorial Information System, the Public

Table 1
Functional traits of rocky reef fishes used to estimate functional diversity. Adapted from Stuart-Smith et al. (2013).

Functional trait	Description	Levels
Maximum length	Species maximum length	Lm20 (less than 20 cm), lm20-40 (between 20 and 40 cm), lm40-60 (between 40 and 60 cm) and lm60 (more than 60 cm)
Trophic group	Species trophic niche	Browsing herbivore, benthic invertivore, planktivore, higher carnivore
Water column position	Species position in the water column	Benthic, demersal, site-attached pelagic, roaming pelagic
Habitat complexity	Habitat use	Typically associated with habitats characterized by low, medium, high complexity
Gregariousness	Intraspecific relationships	Solitary, paired, forming schools

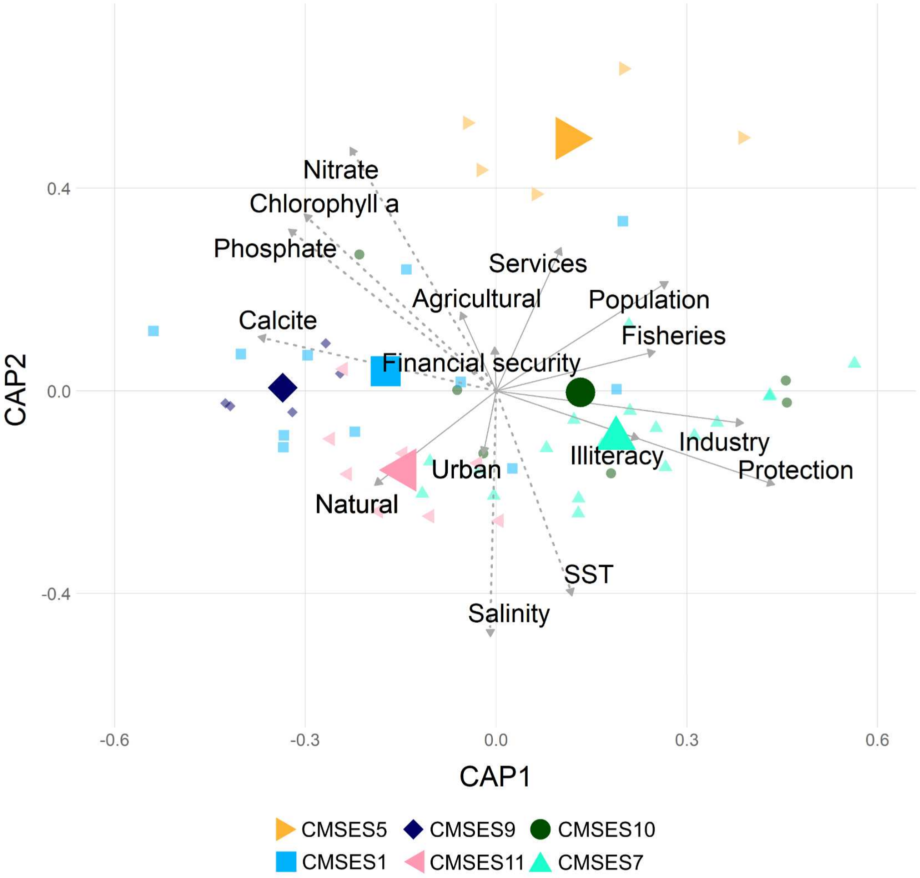


Fig. 3. Distance based-redundancy analysis (db-RDA) biplot of weighted average scores for species beta diversity constrained by the socioeconomic (grey solid lines) and marine environmental variables (grey dashed lines). Population – population density and young people with a university degree; Illiteracy – illiteracy rate; Fisheries – tonnes of fish landings and fishing vessels density; Financial security – annual income per inhabitant and employment rate; Services – people employed in service sector; Industry – people employed in industry; Urban – urban land uses; Natural-natural land uses; Agricultural – agricultural land uses; Protection – surface of protected area; Nitrate-nitrate concentration; Calcite – calcite concentration; Phosphate – phosphate concentration; Chlorophyll *a* – mean chlorophyll *a* concentration; SST – mean sea surface temperature.

Service State Employment and the Ministry of Agriculture, Fisheries and Food. Then, we performed a principal component analysis (PCA) of socioeconomic variables to reduce redundant information of each socioeconomic aspect, and to identify the new variables that characterize the differences between CMSESs (see Table S3). To name the new variables, we used those socioeconomic variables that had the highest square cosines and thus were the most relevant in explaining those PCA components with eigenvalue higher than one (Kaiser, 1960). The 24 original socioeconomic variables were reduced to ten variables distributed in the five socioeconomic aspects studied: demographic (population and illiteracy rate), economic (people employed in service sector, financial security and people employed in industry), land-use variables (urban, natural and agricultural land uses), sea-use variable (fisheries) and environmental protection (surface of protected area). See Table S3 of Supplementary Material for additional information. In addition, we used six marine environmental variables that were found to characterize the CMSESs in Andalusia: primary productivity (mean chlorophyll *a* concentration), nutrients (nitrate and phosphate concentration), inorganic carbon (calcite concentration), salinity and sea surface temperature (mean sea surface temperature) (Lazzari et al., 2019).

3.2.3. *Social-ecological relationships*

To examine the relationships between beta diversity and socioeconomic and marine environmental variables, we performed distance-based redundancy analyses (db-RDA; Legendre and Anderson, 1999). This method is similar to redundancy analysis but based on a non-Euclidean distance measure. In this study, we used the Bray-Curtis dissimilarity to calculate the species and functional beta diversity. To perform the db-RDA analysis, we used the socioeconomic and marine environmental variables as explanatory variables and the beta diversity matrices of species and functional traits as response variables. We used the *capscale* functions of 'vegan' R package (Oksanen et al., 2019), to conduct the db-RDA analyses.

To inspect the relationships between alpha diversity and socioeconomic and marine environmental variables, we performed redundancy analyses (RDA; Legendre and Anderson, 1999). We used the socioeconomic and marine environmental variables as explanatory variables and the species and functional alpha diversity indices as response variables. To conduct the RDA analyses, we used the *rda* functions of 'vegan' R package (Oksanen et al., 2019), and the 'ggplot2' R package (Wickham, 2016) to perform the graphical representations (R Core Team, 2018).

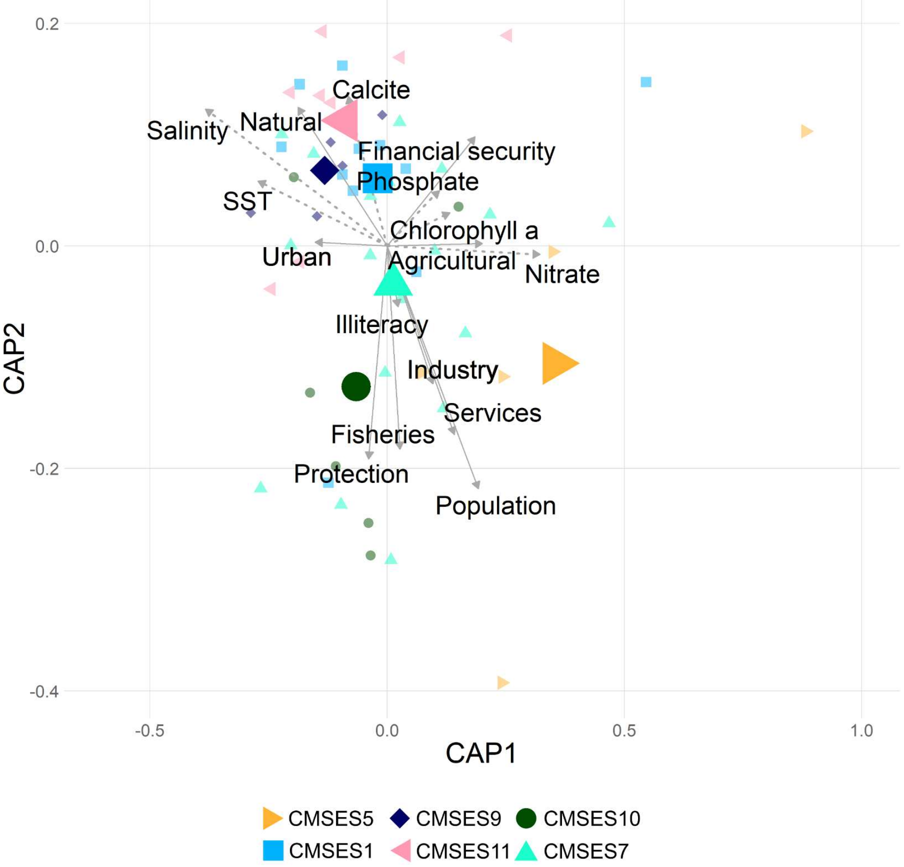


Fig. 4. Distance based-redundancy analysis (db-RDA) biplot of weighted average scores for functional beta diversity constrained by the socioeconomic (grey solid lines) and marine environmental variables (grey dashed lines). Population – population density and young people with a university degree; Illiteracy – illiteracy rate; Fisheries – tonnes of fish landings and fishing vessels density; Financial security – annual income per inhabitant and employment rate; Services – people employed in service sector; Industry – people employed in industry; Urban – urban land uses; Natural-natural land uses; Agricultural – agricultural land uses; Protection – surface of protected area; Nitrate-nitrate concentration; Calcite – calcite concentration; Phosphate – phosphate concentration; Chlorophyll *a* – mean chlorophyll *a* concentration; SST – mean sea surface temperature.

4. Results

We found that species and functional beta diversity was related to different socioeconomic and marine environmental variables ($F = 1.490$, $p = 0.001$, Adjusted $R^2 = 0.131$ *and* $F = 1.420$, $p = 0.003$, Adjusted $R^2 = 0.114$, respectively). Species beta diversity of CMSES9 was associated with calcite concentration, while species beta diversity of CMSES7 and CMSES10 was associated with a higher surface of protected areas, a higher rate of illiteracy people, and a higher rate of people employed in industry (Fig. 3). The species beta diversity of CMSES5 was associated with those places where the rate of population employed in service sector was high. By contrast, the species beta diversity of CMSES11 was related to natural land uses (Fig. 3).

Functional db-RDA showed that functional beta diversity of CMSES1, CMSES9, and CMSES11 was related with similar socioeconomic and marine environmental variables: high sea surface temperature, higher levels of salinity and calcite, and a higher surface of natural land uses (Fig. 4). Functional beta diversity of CMSES10 was associated with higher surfaces of protected areas and fisheries (Fig. 4). Functional beta diversity of CMSES5 was associated with a higher human population density, higher rates of people employed in industry and service sector and higher nitrate concentration. Finally, the functional beta diversity of CMSES7 did not show any preferential association with socioeconomic or environmental variables (Fig. 4).

Regarding species and functional alpha diversity, we found that the species and functional alpha diversity indices were associated with different socioeconomic and marine environmental variables ($F = 1.666$, $p = 0.033$, Adjusted $R^2 = 0.170$; Fig. 5). Species richness was positively related to natural land uses, higher protected surface, higher salinity, and sea surface temperature; whereas it was negatively associated with higher concentrations of nitrate, chlorophyll *a* and phosphate (Fig. 5). Functional evenness was positively associated with higher financial security (i.e., high annual income per inhabitant and high employment rate) and people employed in service sector; whereas it was negatively associated with higher urban land uses and a higher rate of illiterate population (Fig. 5).

5. Discussion

Our study showed how species community and functional structure are partially associated with socioeconomic and marine environmental variables that characterize CMSESs. This result supports the voices claiming that biodiversity assessments should be included in social-ecological systems (Rissman and Gillon, 2016; Mehring et al., 2017).

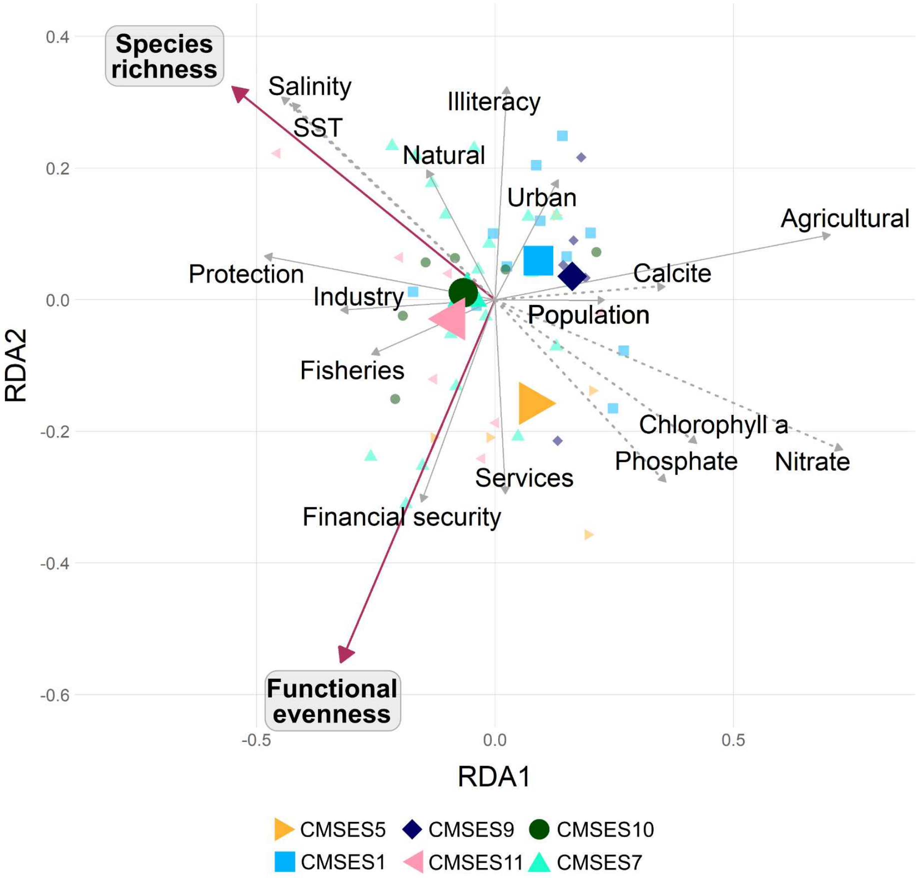
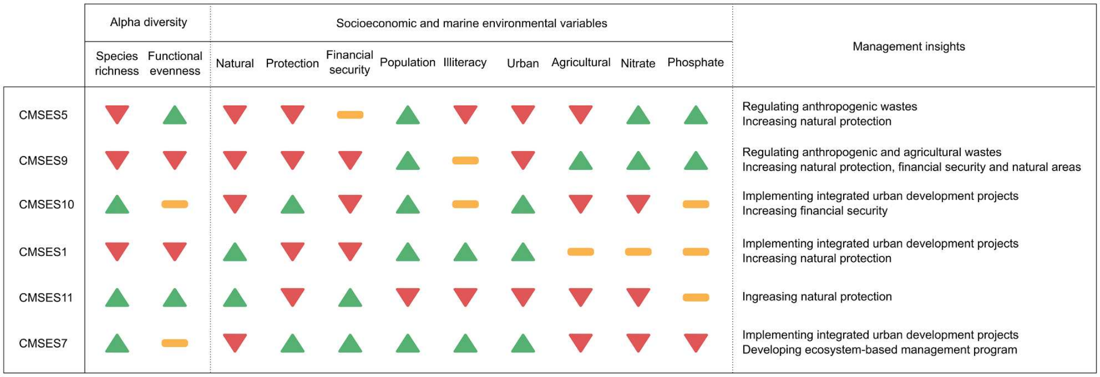


Fig. 5. Redundancy analysis (RDA) biplot of weighted average scores for species and functional alpha diversity (pink arrows) constrained by the socioeconomic socioeconomic (grey solid lines) and marine environmental variables (grey dashed lines). Population – population density and young people with a university degree; Illiteracy – illiteracy rate; Fisheries – tonnes of fish landings and fishing vessels density; Financial security – annual income per inhabitant and employment rate; Services – people employed in service sector; Industry – people employed in industry; Urban – urban land uses; Natural-natural land uses; Agricultural – agricultural land uses; Protection – surface of protected area; Nitrate-nitrate concentration; Calcite – calcite concentration; Phosphate – phosphate concentration; Chlorophyll *a* – mean chlorophyll *a* concentration; SST – mean sea surface temperature.



	Alpha diversity		Socioeconomic and marine environmental variables									Management insights
	Species richness	Functional evenness	Natural	Protection	Financial security	Population	Illiteracy	Urban	Agricultural	Nitrate	Phosphate	
CMSES5	▼	▲	▼	▼	▬	▲	▼	▼	▼	▲	▲	Regulating anthropogenic wastes Increasing natural protection
CMSES9	▼	▼	▼	▼	▼	▲	▬	▼	▲	▲	▲	Regulating anthropogenic and agricultural wastes Increasing natural protection, financial security and natural areas
CMSES10	▲	▬	▼	▲	▼	▲	▬	▲	▼	▼	▬	Implementing integrated urban development projects Increasing financial security
CMSES1	▼	▼	▲	▼	▼	▲	▲	▲	▬	▬	▬	Implementing integrated urban development projects Increasing natural protection
CMSES11	▲	▲	▲	▼	▲	▼	▼	▼	▼	▼	▬	Ingreasing natural protection
CMSES7	▲	▬	▼	▲	▲	▲	▲	▲	▼	▼	▼	Implementing integrated urban development projects Developing ecosystem-based management program

Fig. 6. Summary of alpha diversity indices, socioeconomic and marine environmental variables related with species and functional alpha diversity and management insights for biodiversity conservation. Green up arrows, yellow lines, and red down arrows represent high, medium, and low values of each variable, respectively. In order to make the results comparative and descriptive, these classes are based on a relative classification of the variables, limited by their 33rd and 66th percentiles. See Fig. S1 of Supplementary Material to visualize the alpha diversity variation among CMSESs.

Until now, the characterization of social-ecological systems has mainly considered environmental and socioeconomic factors (e.g. Castellarini et al., 2014; Martín-López et al., 2017; Lazzari et al., 2019), ecosystem services (Hamann et al., 2015; Sinare et al., 2016; Leenhardt et al., 2017) or land-uses (Alessa et al., 2009); but biodiversity has remained underexplored when characterizing social-ecological systems. Few studies have analyzed biodiversity patterns to characterize social-ecological systems. For example, Hanspach et al. (2016) found that species richness of butterflies, birds, and plants differ between social-ecological units in Transylvania (Romania). Based on these results, they suggest that different conservation measures should be implemented according to the biodiversity characteristics of each social-ecological unit. The lack of biodiversity assessments in social-ecological research of marine and coastal systems is even more remarkable than in terrestrial land systems (Rissman and Gillon, 2016). In marine systems, Leslie et al. (2015) and Mahboubi et al. (2015) used an expert-survey approach to assess biodiversity with a social-ecological approach; however, they did not empirically evaluate whether biodiversity varied among existing social-ecological systems. Therefore, to our best of knowledge, this study is the first one characterizing alpha and beta species and functional diversity in CMSESs.

This study advances social-ecological research on coastal and marine systems by assessing littoral fish biodiversity in six Andalusian CMSESs. We focused on both beta and alpha diversity of species community and functional traits because these metrics provide different information. While beta diversity informs about the different species/functional composition among sites, alpha diversity informs about the number of different species/functions in a site and how the species/functions are balanced in terms of abundance. Our study shows that the heterogeneous biological and functional beta and alpha diversity of CMSESs in Andalusia might be partially explained by the differences in socioeconomic and environmental variables characterizing the CMSESs, which might have implications for biodiversity conservation. For example, species and functional beta diversity of CMSES5 and CMSES9 were associated with different socioeconomic and environmental characteristics (Fig. 3 and Fig. 4). While beta diversity of CMSES5 was related to high concentrations of nitrates, a high human population density, and a high percentage of people working in the service sector; functional beta diversity of CMSES9 was related to high concentrations of calcite, and natural land uses. If the management of biodiversity in CMSES5 and CMSES9 focuses only on species richness, which is low in both CMSES, it might neglect the differences in the community functioning that might result from the different marine environmental and socioeconomic characteristics (Fig. 5). Therefore, one of the challenges of biodiversity conservation in coastal and marine systems is to design and develop management actions that are adapted to the different socioeconomic and environmental variables that characterize CMSESs (Fig. 6). For example, while the management of CMSES5 should consider the pollution derived from the nitrates used in agriculture and should foster increasing the surface of natural land uses; these management actions might be insufficient in CMSES9 (Fig. 6).

We also found that although some CMSESs such as CMSES1 and CMSES11, shared similar relationships between socioeconomic and environmental characteristics and functional beta diversity (Fig. 3 and Fig. 4), they presented different species and functional alpha diversity (Fig. 6). Functional beta diversity of both CMSESs was related to those areas representing natural land uses that also have higher values of calcite concentration, salinity, and phosphate concentration. However, species and functional alpha diversity presented opposite patterns as result of different socioeconomic and environmental conditions (Fig. 5; Fig. 6). The different environmental and socioeconomic conditions that relate to species and functional alpha diversity in CMSES1 and CMSES 11 might entail different management actions in these CMSESs. For example, to counteract the low species richness and functional evenness in CMSES1, management actions can promote integrated urban development to face the high population density and high urban land uses (Fig. 5; Fig. 6). Also, to preserve the high alpha diversity in CMSES11 while increasing in CMSES1, marine and terrestrial protection might be necessary in both CMSES.

We also found that those CMSESs characterized by a high percentage of protected areas, i.e., CMSES7 and CMSES10, host higher levels of species richness but medium functional evenness (Fig. 6). This result supported the findings of a recent study conducted in western Mediterranean that demonstrate that marine protected areas are more efficient in increasing fish biomass than in protecting species and functional diversity (Sanabria-Fernandez et al., 2019). Our study argues that management measures in western Mediterranean should focus on developing ecosystem-based management programs that consider both the human and ecological dimensions.

Given the proximity of the sampling sites and relatively uniform habitat characteristics of the Andalusian coastline, our results suggest that marine biodiversity is, at least in part, shaped by local social and environmental factors and that alpha and beta diversity matters in characterizing social-ecological systems. The biodiversity inclusion in the identification and characterization of marine social-ecological systems promotes the comprehensive integration of multiple socio-economic, environmental, and biological dimensions in the analysis of CMSESs.

6. Conclusions

This research showed that incorporating biodiversity metrics in social-ecological studies and considering social-ecological variables when assessing biodiversity, can be a promising strategy to design and develop more effective conservation and management actions in coastal and marine systems. Our study demonstrated that environmental and socioeconomic variables explain the fish community variation among CMSESs in alpha and beta diversity and their functional traits. By providing empirical information about the marine biodiversity of the Andalusian CMSESs, we hope to stimulate interdisciplinary social-ecological thinking in marine biodiversity conservation. In this sense, protection of marine biodiversity should consider not only the existing biodiversity in the Andalusian coastline but the socioeconomic and environmental variables underpinning such differences.

Acknowledgments

We thank all the RLS divers who have contributed to biological data collection in the Andalusian coast and all the dive centers that made the sampling possible. We also appreciate the constructive comments from Dr. Rick D. Stuart-Smith, Dr. João Carlos Marques and two anonymous reviewers, which helped improve the quality of our manuscript. This study was supported by the Project MARINERES, CGL2013-49122-C3-1-R of the Spanish Ministry of Economy and Competitiveness.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2019.105786.

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