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The influence of climate change on the coastal risk landscape of the Catalan coast

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The influence of Climate Change on the coastal risk landscape of the Catalan coast

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Para mi madre

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Contents

Abstract

Coastal areas concentrate very high socio-economic and natural values, which will be highly threatened by climate change, particularly by sea-level rise (SLR). Given the intrinsic characteristics of this zone, appropriate risk management requires a holistic analysis in which the multiple components of the coastal system are taken into account. This has been addressed by applying the concept of coastal risk landscape, which can be defined as the set of all the risks to which the coastal zone is exposed. In this work, the two most relevant SLR-driven hazards in terms of induced coastal impacts, erosion and inundation, have been analysed. The multiple functions provided by the coastal system open a wide spectrum of possible management options in general, and of adaptation strategies in particular, as a function of the policy target. This work focuses on the analysis of SLR-induced consequences (impact and adaptation) on recreational and natural functions of the coast due to their importance for the Mediterranean in general, and the Catalan coast in particular, and because they represent well the range of potential targets for coastal management, economy vs. environmental protection.

From the recreational point-of-view, beaches are the main asset to be managed so that any variation in the carrying capacity will be translated into an impact on their recreational-tourist use. The expected shoreline-retreat, both due to the current evolution rates and SLR-induced erosion, will imply a reduction in the optimal beach width to support the carrying capacity on beaches, an important factor for coastal tourism development, leading to an expected significant and growing economic impact in the next decades. Obtained results show that the Catalan coast is highly vulnerable to erosion and accelerated SLR exacerbates this adverse situation, although with significant spatial variation. Costa Barcelona is the most affected under current evolution rates finding here erosional hotspots such as the Mareme comarca (excluding the Ebro Delta). When SLR is considered, severely affected municipalities will appear within the Costa Brava whose future beach evolution will result in a significant decrease in the potential demand. In these areas, efficient adaptation measures will be required to maintain future carrying capacity within a certain range to properly support the economic contribution of the coastal tourism sector.

From the environmental perspective, the induced SLR-impact is analysed in terms of the potential damage on existing ecosystems. Flood-prone areas and potential damages

are assessed taking into account the intrinsic resilience and adaptive capacity of some coastal habitats in the face of SLR. Obtained results show that Catalonia has a low sensitivity to SLR-inundation due to its coastal configuration except for low-lying areas (Gulf of Roses, Llobregat Delta and Ebro Delta), which in turn concentrate the highest natural values of the Catalan coast. In spite of their physical vulnerability, existing habitats have a natural adaptation capacity, which permits to maintain providing ecosystem functions although under a modified landscape. In these areas, adaptation strategies based on promoting the natural resilience of coastal habitats to SLR can allow for open up a whole range of adaptation strategies to shift the management perspective to environmental protection and conservation.

Resumen

Las zonas costeras concentran un elevado número de valores tanto socio-económicos como naturales, los cuales se verán fuertemente amenazados por el cambio climático, particularmente por la subida del nivel del mar. Dada las características intrínsecas de estas zonas, se requiere una gestión adecuada del riesgo desde una perspectiva global donde se tienen en cuenta sus múltiples componentes. Por ello, el análisis realizado se enfoca a través del uso del concepto *paisaje del riesgo costero*, siendo el conjunto de riesgos a los que se ve sometida la zona costera. En este trabajo, las dos amenazas más relevantes desde el punto de vista del impacto producido, erosión e inundación costera, han sido analizadas. Las múltiples funciones que ofrece el sistema costero abren un amplio espectro de posibles opciones de gestión en general, y de estrategias de adaptación en particular, en base a los criterios políticos establecidos. Este trabajo se centra en el análisis de las consecuencias inducidas por la subida del nivel del mar (impacto y adaptación) en las funciones recreativas y naturales de la costa debido a su importancia para el Mediterráneo en general, y para la costa catalana en particular, representando así un rango amplio de objetivos potenciales en la gestión costera, la economía frente a la protección del medio ambiente.

Desde el punto de vista del uso recreativo del litoral, las playas son el principal recurso a gestionar por lo que cualquier variación en su capacidad de carga se verá traducida en un impacto en la actividad turístico-recreativa de estas. El retroceso esperado de la línea de costa, tanto por las tasas de evolución actuales como por la erosión inducida por un incremento del nivel del mar, implicará una reducción en el ancho efectivo de las playas del litoral catalán para poder soportar su capacidad de carga, un factor clave para el desarrollo del turismo costero, causando un impacto económico significativo y creciente en las próximas décadas. Los resultados obtenidos indican que la costa catalana es altamente vulnerable a la erosión, la cual se verá incrementada por la subida del nivel del mar. Debido a que las mayores tasas actuales de erosión se encuentran en el área de Costa de Barcelona (excepto el Delta del Ebro), sus playas serán las que se vean más afectadas en cuanto a retroceso costero. Por el contrario, considerando los valores de subida del nivel del mar, la evolución futura de las playas de la Costa Brava se verá fuertemente afectada, resultando en una reducción significativa de su demanda potencial. En estas zonas, se requerirán medidas eficientes de adaptación para mantener la futura capacidad

de carga en un determinado rango para sostener la contribución económica de las actividades relacionadas con el turismo costero.

Desde el punto de vista ambiental, el impacto inducido por un aumento del nivel del mar es analizado en términos de afectación potencial de los ecosistemas existentes. Para ello, se evalúa la superficie de hábitats afectados y el daño causado considerando la resiliencia de algunos hábitats costeros. Los resultados obtenidos muestran que la costa catalana tiene una baja sensibilidad a la inundación costera dado su elevado frente de playa, exceptuando el Golfo de Rosas, el Delta del Llobregat y el Delta del Ebro, siendo estas las áreas con mayor valor ambiental. A pesar de su vulnerabilidad, los hábitats existentes tienen una capacidad natural que permite mantener la provisión de los servicios ecosistémicos a la sociedad, aunque el paisaje costero se vea modificado. En estas zonas, el diseño de estrategias de adaptación basadas en promover la resiliencia natural de los hábitats supondrá una oportunidad para cambiar el modelo de gestión hacia la protección y conservación medioambiental.

Chapter 1

Introduction

1.1. Generalities

Climate change (CC) and, in particular sea-level rise (SLR), is one of the main threats to global coastal systems, with a direct consequence of increased coastal hazards (Wong et al., 2014). If we also consider the population growth and accumulation of assets in the coastal zone due to the coastward migration and urban sprawl (e.g. Small and Nicholls, 2003), this will result in an intensification of coastal damages along this century (e.g. Neumman et al 2015). All this justifies the need to include CC-induced risk assessment within coastal management strategies (Losada et al., 2019).

A large (or even, the largest) contribution to the CC-induced risk in the coastal zone lies in the high importance of exposed assets which may be affected in the near future. On the one hand, coastal regions generate higher GDP per inhabitant than non-coastal ones (Eurostat, 2015). In this sense, coastal regions along Europe's coastline generated almost €6,400 billion of GDP representing approximately 43% of its total GDP (European Commission, 2019), with more than €305 billion GDP being at risk under a 1 m SLR (Policy Research Corporation, 2009a). On the other hand, coastal ecosystems are among the most productive systems in the world providing multiple ecosystem services indispensable to the human wellbeing (MEA, 2005). In fact, coastal environments may contribute 77% of the global ecosystem service value estimated as $125 trillion/yr in 2011 (Costanza et al., 1997, 2014). However, the potential damage due to SLR to the ecosystem service value in Europe could be about €2.9 billon/yr by 2050 (Roebeling et al., 2013).

In this general context, CC becomes a real threat that requires adaptation given that mitigation alone is insufficient to prevent expected impacts (Biesbroek et al., 2010). This need for adaptation has attracted the attention of politicians and research funding agencies becoming one key issue in environmental research and sustainable development (Khan and Roberts, 2013). The European Climate Change Adaptation Strategy recognises coastal areas as one of the most at risk being priority areas to CC adaptation leading to enhance preparedness and response skills at local, regional, national and EU levels (European Commission, 2013). In this context, adaptation has become a priority objective for Spain given its high vulnerability to CC adopting the National Adaptation Plan to Climate Change (PNACC) and the Spanish Strategy for Coastal Adaptation to Climate Change in 2006 and 2016, respectively. This framework stablished that adaptation must be integrated into Spanish Laws which the most important legal instrument for addressing CC on coastal areas is the Law 2/2013 for the protection and sustainable use of the coast amending the Law 22/1988 that regulated the coastal management over 25 years.

The Mediterranean coastline can be considered as one of the hotspots worldwide where there is a growing urgency to improve our understanding of the effects of CC-impacts on society and the environment and how we may adapt to such changes (Cramer et al., 2018; Fatorić and Chellerri, 2012; Sánchez-Arcilla et al., 2008, among others). Several initiatives such as the Protocol on Integrated Coastal Zone Management in the Mediterranean (ICZM, UNEP/MAP/PAP, 2008) included a specific chapter on natural hazards and recommended signed countries to undertake risk assessments to address the impacts of natural hazards, and CC in particular. In 2016, the Barcelona Convection Parties, including Spain, adopted the Mediterranean Strategy for Sustainable Development 2016-2025 (UNEP/MAP, 2016) with the objective of increasing scientific knowledge and raising awareness as well as developing technical capacities to deal with CC.

Given the importance of assessing properly the coastal risk when designing coastal management plans, one possible approach is based on the concept of coastal risk landscape, which can be defined as the set of all risks to which the coastal zone is exposed (Ballesteros, 2017). Under this perspective, the conceptual framework SPRC captures the mains aspects required for a robust coastal risk assessment describing how a given risk propagated from the source to the receptor whose impact induces the consequences (e.g., Narayan et al., 2014; Zanuttigh et al., 2014). In this thesis, the IPCC terminology has been followed by conceptualizing the coastal system as both natural and human systems where coastal features and ecosystems are included together with build environment and human activities (Wong et al., 2014).

Within this context, the main motivation of this thesis is the assessment of SLR-induced impacts, associated to two main coastal hazards, i.e. erosion and inundation. In spite of the large number of coastal functions and values along the Catalan coast, here only the recreational and natural functions are analysed. They have been selected based on their importance from the economic and environmental standpoints, and their complementarity, since they will represent the two ends of the economy-environment spectrum. In general, along the Catalan coast, areas of high economic values are associated with large tourism/recreation development and relatively low environmental/natural values and vice versa (Brenner et al., 2010). This would drive different adaptation strategies depending on the targeted function.

1.2. The Catalan coast

Catalonia is an autonomous region located on the NE Spanish Mediterranean coast (Fig. 1.1). It occupies 32,105 km^2 with a coastline of 600 km of which 270 km are beaches. According to Brenner (2007), approximately 46% of the total coastal land is urban, 6% is protected against urbanization (but not excluded for agricultural purposes), 8% is non-urban and 40% is protected under the regional Plan of Spaces of Natural Interest in Catalonia (PEIN).

Administratively, the Catalan coast comprises 70 municipalities, which compromises approximately 23% of the total territory, and are grouped into 12 *comarcas* (territorial units similar to counties) (Fig. 1.1 and Table A1 in Annex A). According to the data from IDESCAT (2016), 62% of the total population inhabits in these coastal regions with an average population density of about 507 people/km^2, without considering Barcelonès where it reaches 15,320 people/km^2. These values are significantly higher than the Catalonia average, which is 234 people/km^2 in 2016, which can be tripled in some municipalities during the summer season.

Socio-economic development of the Catalan coast is based on typical coastal activities such as commerce, agriculture and residential development, with tourism being the predominant economic activity (Sardá et al., 2005) contributing around the 11% of the Gross Domestic Product (GDP) (Duro and Rodríguez, 2011). At the same time, coastal comarcas support 70% of the total accommodations in Catalonia (hotel, cottages and camping places) (IDESCAT, 2016). These facts indicate the importance of beaches in the economic development of the area.

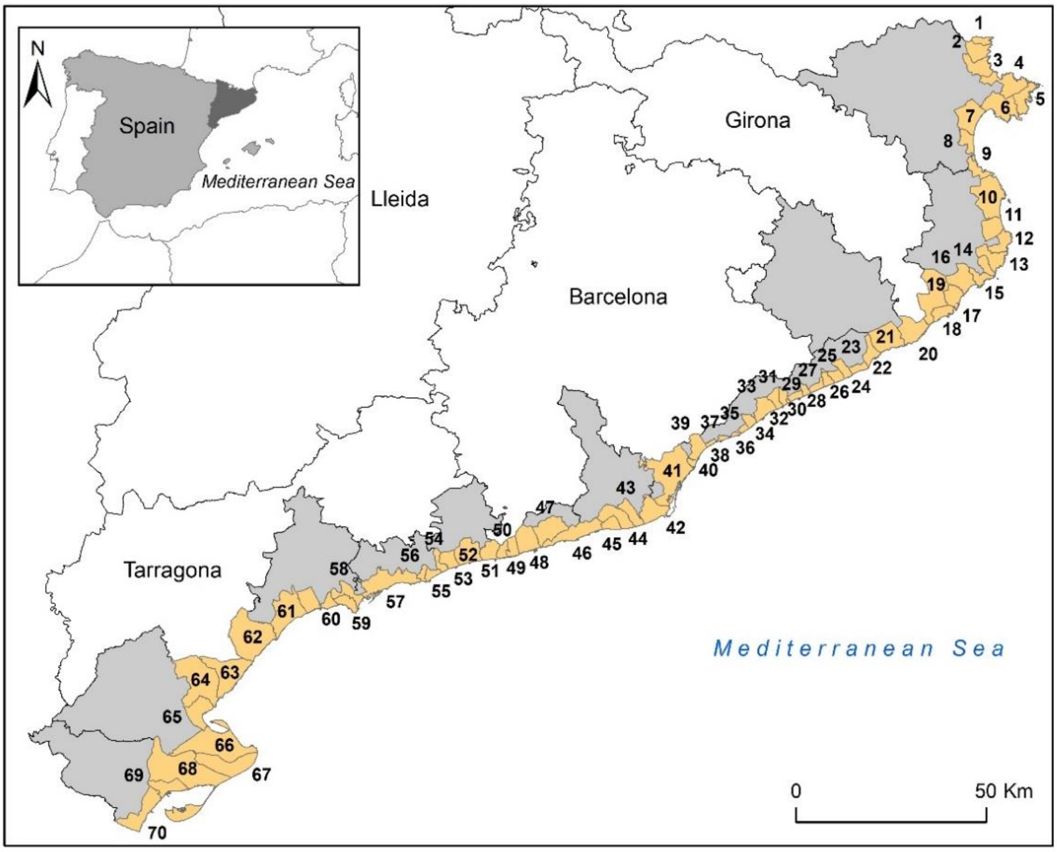

Figure 1.1. Study area and administrative units (number codes in Table A1 in Annex A).

Regarding the landscape and natural areas, there are several natural protected areas within the Catalan coast, largely located in the northern (Cap de Creus and Gulf de Roses) and southern regions (Ebro Delta). In fact, 23% of the total protected areas in Catalonia are within the coastal comarcas. If coastal ecosystem services are translated into economic values, 4.3% of the annual income should be added to the total economic wealth of coastal citizens (Brenner et al., 2010). However, according to Greenpeace (2018), Catalonia is the autonomous region with the highest percentage of degraded coast due mainly to human actions where more than a quarter of its coastline has no capacity to provide such goods and services. These facts reveal the substantial contribution of natural areas to the well-being of coastal communities that must be considered as an important asset in the future, whose conservation and protection should be included in future management strategies.

Coastal erosion and inundation have been considered as the two most relevant hazards in Catalonia due to their induced impacts (Barlonas and Llasat, 2007; CADS, 2008; Jiménez et al., 2011). Coastal damage has significantly increased at a rate of approximately 40% per decade over the last 50 years in the absence of a general increase in marine storm-induced hazards (Jiménez et al., 2012). This is the result of an increasingly exposure along the coast and a progressive coastal retreat where about 65% of beaches are subjected to erosion with an average retreat rate of -1.6 m/yr (Jiménez and Valdemoro, 2019), resulting in an average evolution rate of about -0.5 m/yr for the entire Catalan sedimentary coastline.

In Catalonia, several milestones related to CC-impacts on coastal areas have been achieved but further work is still needed. Coastal risks were included in a specific chapter of the RISKCAT report (CADS, 2008). The current situation and future developments relating to the CC-effects on natural and humans systems in Catalonia have been analysed in the last report of the Catalan Office of Climate Change (Generalitat de Catalunya, 2016). Concerning coastal management policies, CADS (2019) suggested some recommendations for sustainable management of marine and coastal environment according to the UN 2030 Agenda to make its conservation compatible with the economic development. And more recently, the Catalan Government approved the Law 8/2020 for the protection and management of the coast that proposes a new model of coastal governance incorporating adaptation measures to the effects of CC.

With this in mind, the Catalan coast is as a good example of coastal hotspot along the Mediterranean due to the combination of multiple stresses and pressures on the natural system, a high exposure and a low adaptive capacity (Jiménez et al., 2017). This adverse situation will be exacerbated if the potential effects of SLR are considered with an estimated SLR-induced additional shoreline retreat between 47 m and 65 m by 2100 for RCP4.5 and RCP8.5 scenarios, respectively (Jiménez et al., 2017).

1.3. Objectives

The main objective of this thesis is twofold: (i) to develop and apply a coastal risk framework to assess SLR-induced impacts due to erosion and inundation on recreational and natural functions provided by the Catalan coast; and (ii) to analyse current status of coastal adaptation to CC, and identify suitable strategies for analysed functions.

In order to achieve this, three partial objectives have been identified:

1. To assess how SLR will affect the recreational function of the coast in terms of the potential impact on the carrying capacity on beaches and the influence on the tourism industry considering different SLR-scenarios.
2. To assess how SLR will affect the natural function of the coast in terms of the potential impact on coastal habitats and the influence on the provision of ecosystem services considering different SLR-scenarios.
3. To analyse current adaptation investments and implemented actions and to propose adaptation strategies for the Catalan coast with the purpose to reduce the vulnerability to the effects of CC.

1.4. Structure of the thesis

Following this first introductory Chapter, the body of this thesis (Chapters 2 to 7) comprises three sections in order to achieve the presented objectives. Finally, the document is closed by Chapter 8 that contains the overall conclusions and recommendations for future works related to this work.

Section 1. Impact of SLR on the recreational function of the coast.

The impact of SLR on the recreational function is analysed in **Chapter 2** by developing a methodology to assess the effect of shoreline evolution on the physical carrying capacity (PCC) on beaches at different territorial scales considering different CC-scenarios. The economic consequences of carrying capacity losses on the tourism sector are analysed in **Chapter 3** given its high importance in the economic development of the region though an Input-Output model downscaled to the comarca level.

Section 2. Impact of SLR on the natural function of the coast.

Similar to the previous section, the SLR-impact is analysed but in this case on the natural function. **Chapter 4** provides a methodology for improved flood-damage assessments due to SLR in natural areas by introducing the capacity of response accounting for the effect of active shorelines to SLR and the likely conversion of some habitats once inundation has occurred. In this section, environmental consequences are analysed in **Chapter 5** by the assessment of the non-market value of natural and seminatural habitats in terms of provided ecosystem services.

Section 3. Adaptation to climate change.

Chapter 6 shows an overview of how coastal adaptation is being financed and implemented in Spain by proposing a methodological framework to analyse (i) how adaptation has been and is currently being funded, (ii) which is the rationale for investments along the territory, (iii) how adaptation investments compare to regular protection costs, and (iv) whether implemented measures are really adaptation ones. Specific adaptation strategies for the Catalan coast based on its functionality are presented in **Chapter 7**.

Finally, **Chapter 8** gives an overview of the main conclusions of this study and its implications for coastal managers. In addition, some suggestions are given for a further research agenda.

Each chapter is designed to be self-contained where the followed methodology for each analysis is presented with its own results and discussions. Some repetitions on study site descriptions or data have been allowed. The idea is to facilitate the understanding of each chapter on its own without having to skim through the thesis to find the required information.

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Chapter 2

López-Dóriga, U., Jiménez, J.A., Valdemoro, H.I., Nicholls, R.J. 2019. Impact of sea-level rise on the tourist-carrying capacity of Catalan beaches. Ocean & Coastal Management, 170, 40-50. https://doi.org/10.1016/j.ocecoaman.2018.12.028

Chapter 4

López-Dóriga, U., Jiménez, J.A. 2020. Impact of Relative Sea-Level Rise on low-lying coastal areas of Catalonia, NW Mediterranean, Spain. Water, 12(11), 3252. https://doi.org/10.3390/w12113252

Chapter 6

López-Dóriga, U., Jiménez, J.A., Bisaro, A., Hinkel, J. 2020. Financing and implementation of adaptation measures to climate change along the Spanish coast. Science of the Total Environment, 712, 135685. https://doi.org/10.1016/j.scitotenv.2019.135685

Impact of sea-level rise on the recreational function of the Catalan coast

Chapter 2

Impact of sea-level rise on the tourist-carrying capacity of Catalan beaches

Adapted from: López-Dóriga, U., Jiménez, J.A., Valdemoro, H.I., Nicholls, R.J. 2019. Impact of sea-level rise on the tourist-carrying capacity of Catalan beaches. Ocean & Coastal Management, 170, 40-50. doi: 10.1016/j.ocecoaman.2018.12.028

2.1. Introduction

It is well known that coastal areas are associated with large and growing concentrations of population, increasing urbanization and socioeconomic activities, which cause interactions between human uses and natural processes. Small and Nicholls (2003) estimated that 23% of the global population lives within 100 km of a shoreline and less than 100 m above sea level. The population density in these near-coastal areas is nearly three times higher than the worldwide average density. These areas also exhibit high rates of population growth (Neumann et al., 2015), and show a high susceptibility to change due to the accumulation of human-induced pressures (e.g., Newton et al., 2012).

Tourism has become one of the main economic engines of coastal areas worldwide. The Mediterranean is the world's leading tourist destination, accounting for about 30% of international tourism globally, with about half of tourist arrivals being in the coastal zone, mainly during the summer season (Plan Bleu, 2016). The majority of coastal tourism is based on the sun-and-sand model and, as consequence; beaches become one of the main resources in providing economic and social values (e.g., Houston, 2013). Within this context, preserving or enhancing beach quality is one of the main goals of coastal managers in maintaining and/or promoting the attractiveness of beaches for tourists and visitors (e.g., Fraguell et al., 2016). One of the main elements in controlling the quality of a beach from a recreational standpoint is the available space for users, which is usually referred to as the physical-carrying capacity (Table 2.1 shows the main definitions and terminology used in this work). In this sense, any meaningful planning of a sun-and-sand destination needs to include a proper assessment of the carrying capacity of existing beaches, which will define the number of users to be accommodated as well as their level of comfort (e.g., De Ruyck et al., 1997; Pereira da Silva, 2002; Valdemoro and Jiménez, 2006). Thus, there is no doubt that the formulation of any sustainable, long-term planning of coastal tourism must include the potential effects of climate change on the quality of resources to be exploited (Hamilton et al., 2005; Moreno and Amelung, 2009a). Among the different climate change-induced impacts, Moreno and Amelung (2009a) concluded that sea level rise (SLR) and/or water availability will be key factors potentially affecting coastal tourism on Mediterranean coasts. With respect to beach quality, SLR will be main source of risk with shoreline retreat and inundation being the most important induced impacts on sandy coastlines (e.g., Nicholls and Cazenave, 2010). Since beach dimensions determine the available surface area for users and services to be provided, morphodynamic processes will condition beach use and exploitation (Valdemoro and Jiménez, 2006). Hence, this work focuses on the potential impacts of SLR-induced shoreline retreat on coastal tourism.

Within the Mediterranean, Spain is a traditional sun-and-sand destination where coastal municipalities have experienced an intense urban and touristic development. According to the Spanish Institute of Statistics, about 26% of foreign tourists visiting Spain chose Catalonia as their destination in 2015. With the exception of the city of Barcelona, the majority of the tourism industry is based on the sun-and-sand model where coastal destinations comprise more than 62% of tourism overnights. (Generalitat de Catalunya, 2015). Hence beaches are the main asset of this economic sector (Rigall-i-Torrent et al., 2011). To this end, we assess the recreational carrying capacity of beaches to accommodate the tourist demand using tourist beach carrying capacity (tourist BCC, see Table 2.1 for definitions).

Within this context, the main aim of this paper is to assess the potential impact of SLR on the recreational carrying capacity of Catalan beaches and hence the potential influence on the sun-and-sand tourism economic model over the coming decades. This is accomplished via three objectives: (1) developing a model of recreational beach utilisation appropriate for Catalonia; (2) developing a shoreline evolution-beach use interaction model; and (3) forecasting the resulting evolution of tourist BCC along the Catalan coast under different SLR scenarios. The practical goal of this research is to support coastal managers in the decision-making process by defining the appropriate mitigation/adaptation measures required for long-term coastal tourism planning.

Table 2.1. Key parameter terminology and definitions.

Carrying Capacity	Amount and type of visitors that can be accommodated within a given amenity area without unacceptable social consequences and without a negative impact on resources (Clark, 1996, Manning and Lawson, 2002; WTO, 1997).
Minimum area per user	Bearable beach surface area per user value without affecting the user-recreational experience. It depends on the beach type and use intensity.
Resting area (also termed "used beach surface" within the text)	Area where most beach users stay and consequently, where umbrellas and sunbeds are usually placed. Beach services are usually located landward of this area unless the beach is too narrow.
Physical-Carrying Capacity (PCC)	Maximum number of users that can physically be accommodated on a beach. It depends on beach dimensions, resting area, and maximum area per user.
Tourist BCC	PCC integrated to a given territorial unit for specific potential users (tourists).

2.2. Study area and data

2.2.1. Study area

The Catalan coast is located in the NE Spanish Mediterranean (Fig. 2.1). Its 600 km-long coastline comprises a large diversity of coastal types, ranging from cliffs to low-lying areas; with about 270 km of beaches. Currently, more than 60% of the beaches along the Catalan coast are impacted by erosion (CIIRC, 2010).

The Catalan coast comprises 70 municipalities and 12 *comarcas* (territorial units comparable to counties) (Fig. 2.1). These *comarcas* comprise about 23% of the territory of Catalonia and 62% of the total population (IDESCAT, 2016). The economy is based on activities such as tourism, commerce, agriculture, and residential development (Sardá et al., 2005). Tourism is one of the main economic sectors providing about 11% of the Catalan GDP (Duro and Rodríguez, 2011), with most accommodations being associated with three tourism brands located along the coast; *i.e.*, Costa Brava, Costa Dorada, and Costa de Barcelona (Generalitat de Catalunya, 2015) (see Fig. 2.2).

Due to its uniqueness within the Catalan coast, the Ebro Delta has been excluded from the current analysis. The delta is intensively used for agriculture, and it comprises important natural resources, which are protected under Natural Park protection laws. Thus, in spite of having more than 50 km of beaches, their recreational use is secondary, with most visits being nature-oriented (Rodríguez Santalla, 2004; Romagosa and Pons, 2017). Due to this, and to avoid the distortion of the analysis from the large delta beach area on the assessment of the regional carrying capacity, we have left out their potential contribution which deserves a specific analysis.

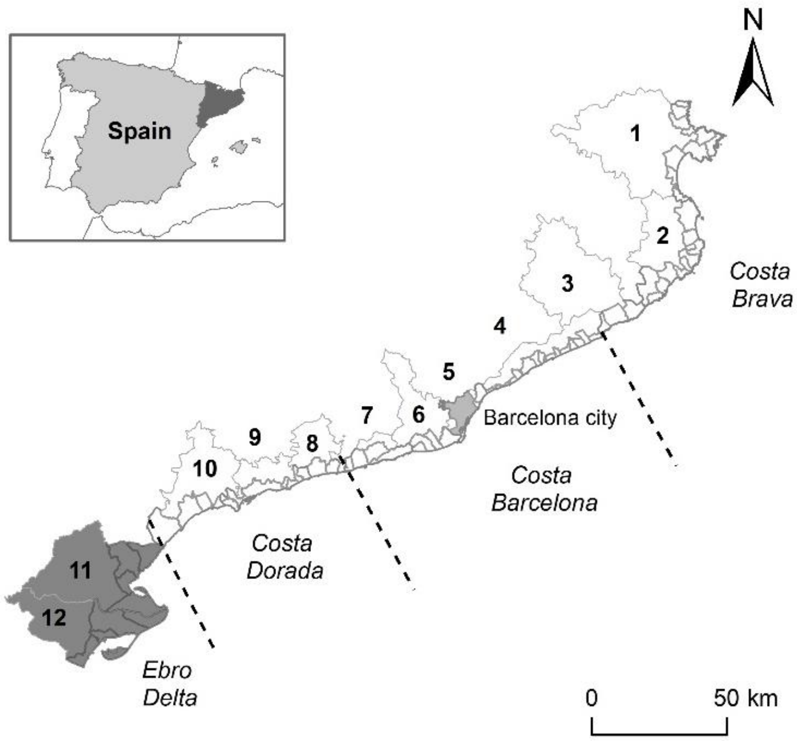


Figure 2.1. The Catalan coast divided into tourism coastal brands (names in italics) and 12 administrative units (comarcas) (from North to South; 1: Alt Empordà; 2: Baix Empordà; 3: Selva; 4: Maresme; 5: Barcelonés; 6: Baix Llobregat; 7: Garraf; 8: Baix Penedés; 9: Tarragonés; 10: Baix Camp; 11: Baix Ebre; 12: Montsià). The smaller divisions within each comarca correspond to the 70 coastal municipalities. Note: Comarcas 11 and 12 were excluded from the analysis.

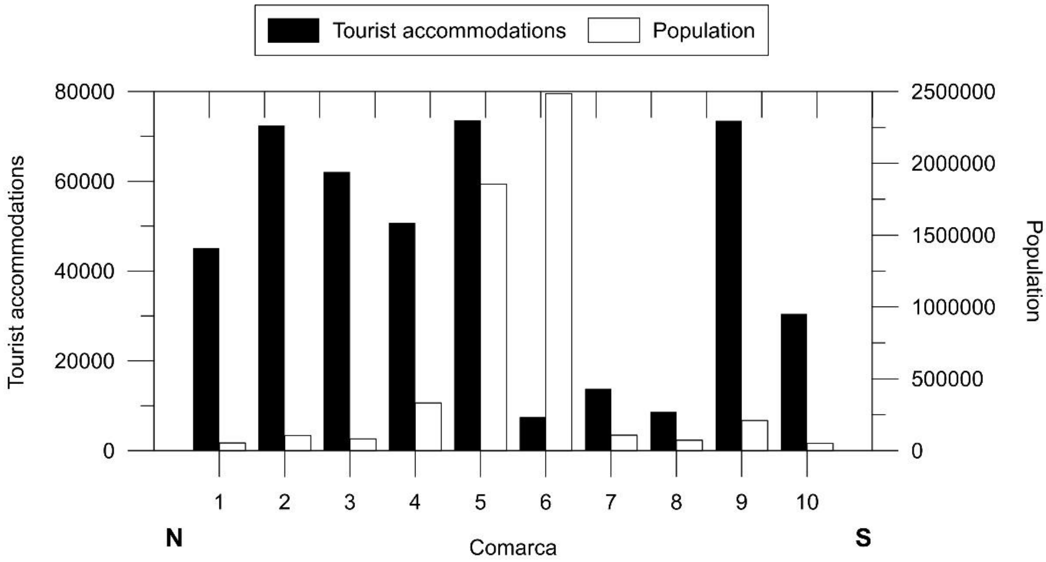


Figure 2.2. Tourist accommodation (bed places) and population values for each comarca along the Catalan coast (see comarcas in Fig. 2.1). Note: Comarcas 11 and 12 were excluded from the analysis.

2.2.2. Data

The data used in this work can be grouped into three types: (1) beach information, including the geomorphology, typology, and intensity of use; (2) socio-economic information related to beach demand; and (3) SLR projections.

2.2.2.1. Beach data

Beach data are used to estimate shoreline dynamics and to characterize beach morphology and typology. In order to assess beach evolution under current climate conditions, we have used a collection of aerial photographs covering the entire Catalan coast taken in 10 flight surveys during the period from 1995 to 2015 by the Cartographic and Geologic Institute of Catalonia (ICGC). These photos are taken at a scale 1:2,500 and have a mean square error smaller than 0.5 m. To characterize current beach characteristics (width, length, and degree of urbanization of the hinterland) we have used the most recent available aerial photograph (2015).

Beaches were classified in terms of the degree of urbanization and in terms of their intensity of use. To this end, in addition to the above-mentioned set of aerial photographs, we used information provided by two public databases: (i) the Beach Guide of the Spanish Ministry of Agriculture, Fish, Food, and Environment (MAPAMA), and (ii) the beach database of the Catalan Government (Generalitat de Catalunya, 2016). Hence, beaches were classified into three categories according to the degree of urban development of the hinterland: (1) urban, (2) semi-urban and (3) rural (see e.g., Ariza et al., 2008); and into three subcategories based on typical intensity of use during the bathing season: (1) high, (2) moderate and (3) low. Each beach category was assigned a minimum area per user (Table 2.2). This value determines the use saturation level and it depends on the beach type, having a low value of 4 m^2/user for urban, highly-frequented beaches (see Alemany, 1984; PAP, 1997; Roca et al., 2008; Valdemoro and Jiménez, 2006; Yepes, 1999).

Table 2.2. Beach typology and minimum area per user associated with their intensity of use.

Beach typology	Characteristics	Intensity of use	Minimum area per user (m^2/user)
Urban	Within the main nucleus of a given municipality. > 60% urbanized hinterland.	high	4
Semi-urban	In residential areas outside the main nucleus of a municipality. 30-60% urbanized hinterland.	high moderate low	4 8 12
Rural	Outside the main nucleus of a municipality. < 30% urbanized hinterland and uninhabited areas.	high moderate low	4 8 12

2.2.2. Potential beach-user data

Data used to characterize potential beach visitors were acquired from official statistics provided by the Statistical Institute of Catalonia (IDESCAT). The used indicator was the number of tourist accommodations (bed places) for each coastal municipality, which corresponds to the sum of the total number of bed places in hotels, cottages, and camping places. It is a proxy for the maximum number of potential tourists, and is used here to calculate the tourist BCC (see definition in Table 2.1). In order to put the tourism demand in context; 9.9 million tourists were registered within the coastal tourism brands during the summer season of 2015 (from June to September), with an average occupancy rate of 65%. Note that these data do not include tourists using unregulated lodging such as Airbnb.

2.2.3. Sea Level Rise

Tidal gauges with records going far enough back to estimate reliable current sea level rise along the Catalan coast are not available (e.g., Marcos and Tsimplis, 2008). Because of this, we have used average sea level rise for the Mediterranean to characterize current conditions. Gomis et al. (2012), reported that the mean sea level in the Mediterranean has been rising at a rate of 0.6 ± 0.1 mm/yr during the period 1948-2000, which is much lower than global rise in mean sea level during the period 1971-2010 (between 1.3 and 2.3 mm/yr, see Church et al., 2013). Marcos and Tsimplis (2008) calculated from the longest available records in the Mediterranean a rising sea-level trend between 1.2 and 1.5 mm/yr, although existing data are biased towards the North coast.

SLR projections are taken from the IPCC 5th Assessment Report (AR5), which are given by best-guess scenarios (50% probability level) for RCP4.5 and RCP8.5 (Church et al., 2013). In addition to this, we have also included a High-end scenario (H+) which has been taken from Jevrejeva et al. (2014) which accounts for uncertainties due to unknowns in polar ice-sheets processes (Antarctica and Greenland) and, it should be equivalent to the RCP8.5 with increased ice-sheet contribution (see also Jackson and Jevrejeva, 2016). For this study, we have used the upper bound given by the projection of sea level at 95% probability (see Jevrejeva et al., 2014). The inclusion of this H+ scenario has been done from the high risk-management perspective to characterize the system response and management requirements under very adverse conditions (e.g., Hinkel et al., 2015). These three scenarios are given by the year 2100 relative to 2000 by 0.53 m, 0.74 m and 1.75 m respectively (Fig. 2.3).

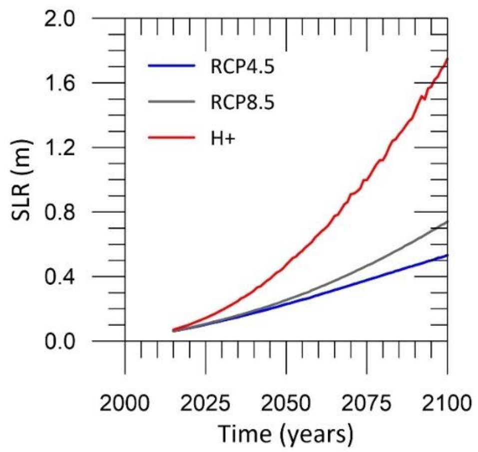


Figure 2.3. SLR scenarios used in this study.

2.3. Methodology

The methodology for this study comprises the following steps: (i) development of the BCC evolution model; (ii) assessment of shoreline evolution and (iii) assessment of the evolution of BCC over time.

2.3.1. Beach-Carrying capacity (BCC) model

This is a model of beach occupancy used to estimate the maximum number of beach users within an administrative unit. It depends on three main parameters: (i) the used beach surface or resting area (see definition in Table 2.1); (ii) the minimum surface per user; and (iii) the users' redistribution capacity within a given territory.

The first element determining the carrying capacity of a beach is the *model of occupation of the space by users*. To this end, we use the concept of resting area (Table 2.1), which is the beach surface occupied by users that depends on the current beach width, the intensity of use, beach exploitation model and tidal conditions. In Spanish Mediterranean beaches, users tend to concentrate in a fringe close to the shoreline, the resting area; that although should ideally be as wide as necessary to comfortably accommodate users, in practice, users in Spanish Mediterranean beaches only concentrate in a 35 to 40 m-wide strip (Alemany 1984; MOP, 1970; Valdemoro and Jiménez, 2006) (see Fig. 2.4). This area is not influenced by tides because it is a microtidal region (25 cm of tidal range). With this type of occupation model, the physical-carrying capacity (PCC) of beaches is given by the maximum number of users to be allocated within the resting area, in such a way that, in the case of eroding beaches but a with a resulting beach wider than the resting zone, BCC is not affected (see e.g. Valdemoro and Jiménez, 2006).

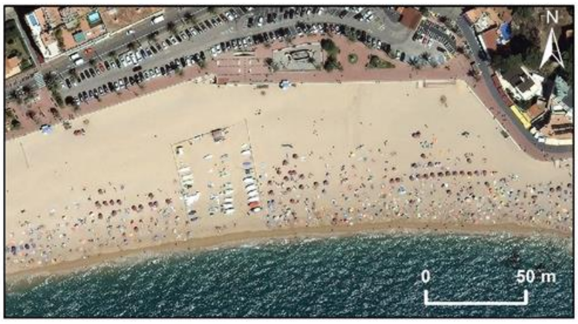


Figure 2.4. Distribution of beach users across a wide beach in Costa Brava, showing the concentration near the shoreline.

To calculate the final allowable number of potential users, it is necessary to consider the beach type that determines the typical density of use and the corresponding minimum beach surface per user. In this work, we have used values characteristic of the area that are specified for each beach along the coast (see Table 2.2).

$$PCC = used\ beach\ area/\ minimum\ surface\ per\ user \tag{2.1}$$

Finally, once the carrying capacity is estimated for each beach, their values are integrated within a given management unit to assess the overall carrying capacity of the unit. This *spatial integration* is done assuming two conditions: (i) each beach maintains its typology and consequently, the allowed minimum surface per user; and (ii) users will redistribute across beaches within a given spatial unit to avoid exceeding the maximum user density. This implies a limitation of user mobility to the scale of integration, in such a way that they will only access beaches within the given spatial unit. This approach mimics the observed influence of distance between accommodations and the coastline on the behaviour of sun-and-sand tourists (e.g., García-Pozo et al., 2011; Pueyo-Ros et al., 2017). Thus, instead of considering alternative beaches for each accommodation within a given distance, we adopt a management-oriented approach in which we associate all accommodations within a given administrative unit with all beaches within such unit. In this study, the minimum integration scale is the municipality, and to simulate an increase in tourist mobility, it can be scaled up to the entire comarca, tourism region brand, or even the entire territory of Catalonia.

Based on these two conditions, the maximum number of beach users in a spatial unit is computed by integrating the capacity of all beaches within the unit but maintaining their individual minimum surface per user.

In order to differentiate the recreational use of the beach by tourists and local residents, results are expressed in terms of the percentage of their demand “served” by beaches within a given unit. Since this study is focused on the potential tourist demand, only the tourist BCC is computed (see Table 2.1). The tourist BCC is calculated for a given spatial integration unit as the ratio (in %) between the integrated PCC of all beaches within the unit and the maximum number of potential tourists of such unit, which is given by the integrated number of tourist accommodations (bed places).

2.3.2. Shoreline evolution

In this study, shoreline evolution rates for each beach are calculated under current conditions and under SLR scenarios. In order to calculate current evolution trends, shorelines were digitized at each beach along the Catalan coast from each available aerial photo. Extracted shorelines were estimated to have an average uncertainty of 2.5 m (CIIRC, 2008). Shoreline displacements were calculated at each beach along a series of control points, with an average spacing of 100 m. The decadal-scale shoreline rate of displacement was then computed by applying linear regression, a technique that removes short-term fluctuations and retains the long-term evolution trend (Dolan et al., 1991). This evolution trend integrates the contribution of all forcing conditions acting on the coast. Since it covers a 20-year period, it can be considered as representative of most probable conditions, from storm to fair-weather-wave states. Each beach was characterized by an integrated shoreline rate of displacement, which was computed by averaging values computed for all control points along the beach. This analysis was done by using the ArcGIS tool “Digital Shoreline Analysis System” (DSAS), v. 4.3 (Thieler et al., 2009).

It has to be noted that the so-obtained evolution rates are used as an empiric model to make shoreline projections under current conditions. The underlying assumption is that no significant changes are affecting littoral dynamics and coastline evolution. This implies that no significant changes in natural conditions will occur (e.g., river sediment supplies, wave climate) and that the current management practices will be maintained.

To calculate the SLR-induced shoreline retreat, we have followed Jiménez et al. (2017), who used the Bruun model. This simple model assumes that the beach profile adapts to the SLR though an upward and landward displacement of the active profile, maintaining the shoreline shape and relative elevation with respect to the new water level (Bruun, 1962). Although some authors question the general validity of this model (e.g., Cooper and Pilkey, 2004), in the absence of a generally-accepted morphological model, it is widely used (e.g., Le Cozannet et al., 2014). Additionally, it provides an indicative estimate of expected shoreline retreat at the regional scale. The induced shoreline retreat, ΔX, is given by the Eq. (2.2) where ΔMWL is the sea-level rise, B is the berm/dune height of the active beach, d_* is the active depth (or depth of closure), L is the across-shore distance from B to d_*, and *Sact* is the averaged inner shelf slope over which the beach profile changes. Ranshinge and Stive (2009) identify the selection of a closure depth representative of this time scale as one of the sources of uncertainties to apply this model. In this work, to overcome this, we adopt the approach of Jiménez et al. (2017), who applied Eq. (2.2) at the regional scale by selecting coastal stretches with an alongshore, homogeneous, inner-shelf slope. This slope has been calculated from the shoreline to 10 m water depth and, thus extending deeper than the medium-term closure depth of the area that has been calculated as about 7 m (CIIRC, 2010). Table 2.3 shows the representative inner shelf slopes used in the different sectors along the Catalan coast. Obtained SLR-induced shoreline retreats are then considered to be constant for all beaches within a given coastal stretch.

$$\Delta X = \Delta MWL \frac{L}{(B + d *)} \approx \frac{\Delta MWL}{Sact} \tag{2.2}$$

Table 2.3. Sections along the Catalan coast (and corresponding *comarcas*) based on the slope of the inner shelf (down to 10 m water depth).

Coastal section	Coastal comarca	Inner shelf slope
Costa Brava	Alt Empordà (1) Baix Empordà (2) Selva (3)	1/87.5
Maresme	Maresme (4) Barcelonès (5)	1/75
Llobregat Costa Dorada	Baix Llobregat (6) Garraf (7) Baix Penedés (8) Tarragonés (9) Baix Camp (10)	1/100

2.3.3. Time evolution of BCC

To assess the BCC temporal evolution along the Catalan coast, we have projected PCC to each selected time horizon by using different scenarios: (i) current conditions, and (ii) assuming an acceleration of SLR according to selected projections.

In the first case, computed shoreline rates of displacement have been extrapolated to the selected time horizon to forecast future beach widths. Hence, we are assuming that no significant changes in governing conditions for coastal dynamics along the Catalan coast will occur over the considered period. Regarding this, it should be noted that existing wave projections for the area over the next century do not show any increase in storminess, and detected changes in mean wave conditions when translated to coastal sediment transport and potential changes in coastline evolution have a high degree of uncertainty (e.g., Casas-Prat et al., 2016).

In the second case, the contribution of climate change to BCC evolution was considered by adding the estimated SLR-induced erosion under each scenario to the estimated baseline shoreline rates of displacement. However, since current projected shoreline evolution rates integrate all acting processes during the 1995-2015 period, they also should include the contribution of the current SLR. Therefore, the Bruun rule was applied to estimate the contribution of current SLR to shoreline erosion during the last 20 years, and was subtracted from evolution rates to obtain the non-SLR contribution. This component is then added to SLR-induced erosion under selected climatic scenarios.

2.4. Results

2.4.1. Shoreline evolution

The statistical distribution of shoreline evolution rates under current conditions for beaches along the Catalan coast is shown in Fig. 2.5. Obtained values are biased towards negative values, reflecting a dominant erosive decadal-scale behaviour during the analysed period (about 65% of the beach length is retreating) at an average rate of displacement of -0.4 m/y. As Jiménez and Valdemoro (2019) pointed, this erosive behaviour is reflecting the integrated effects of natural dynamics and human influence in the territory. Main human forcings are related to variations in sediment supply to beaches and perturbations in sediment transport patterns due to coastal works, with special influence of existing marinas. In fact, largest shoreline displacement rates (both negative and positive) showed in Fig. 2.5, correspond to sites largely affected by the presence of obstacles locally modifying littoral dynamics such as in the surrounding of marinas along the Maresme coast (see also Ballesteros et al., 2018); and to hotspots in deltaic areas suffering of river sediment input decrease (Jiménez et al., 2018; Rodríguez-Santalla and Somoza, 2019).

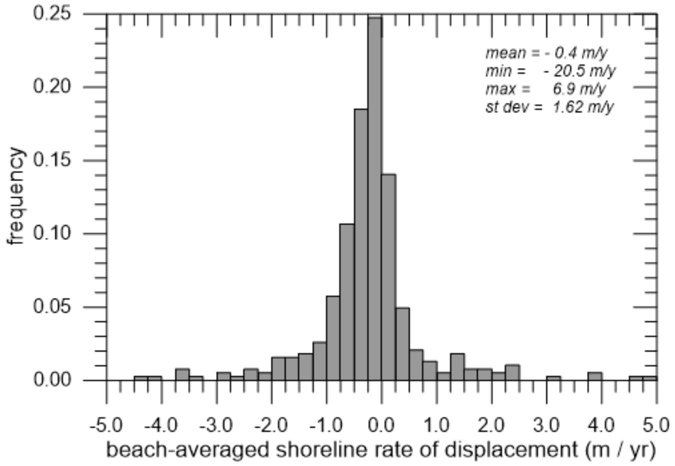


Figure 2.5. Histogram of beach-averaged shoreline evolution rates during the 1995-2015 period along the Catalan coast.

These calculated evolution rates are the integrated result of natural littoral dynamics and human action on the coast during the analysed period. Thus, it has to be considered that during this period; about 5 millions of m^3 of sand have been supplied to the Catalan coast to try to mitigate local stability problems (see Jiménez and Valdemoro, 2019). This implies that the natural background erosion rate should be higher than the calculated one, with the "excess" of erosion being equivalent to that required to remove the supplied volume. In a recent study on the performance of nourishment operations along the southern part of the Catalan coast (Tarragona province) during the last 20 years, Galofré et al. (2018) evaluated this excess of erosion about -0.1 m/y.

Fig. 2.6 shows the SLR-induced shoreline retreat of a representative part (comarcas 6 to 10) of the Catalan coast for the SLR scenarios. As can be seen, the average SLR-induced retreat is projected to be almost the same in 2050 for RCP4.5 and RCP8.5 scenarios (around 20 m), whereas they significantly differ by 2100 due to the expected acceleration in sea level rise under RCP8.5 (47 m and 66 m for RCP4.5 and RCP8.5, respectively). For the H+ scenario, the calculated retreat is about two times larger than those associated with other RCP scenarios in 2050 and three times larger in 2100 (see also Jiménez et al., 2017). Table 2.4 shows the estimated shoreline SLR-induced retreats to be applied to each sector along the coast.

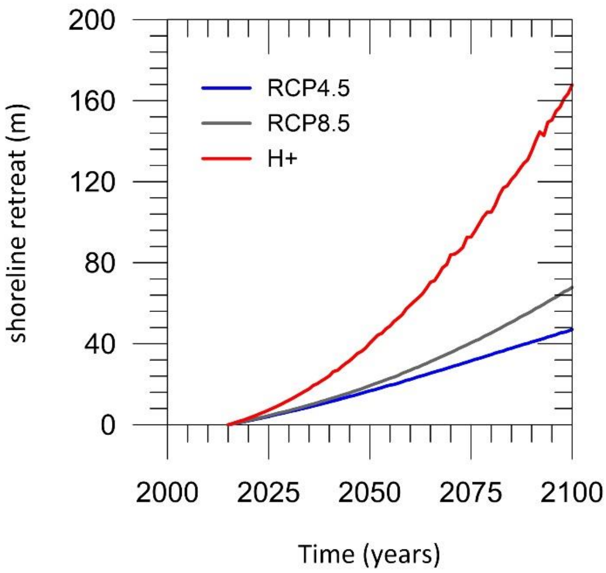


Figure 2.6. SLR-induced shoreline retreat for the southern comarcas (6 to 10 in Table 2.3) of the Catalan coast under selected SLR scenarios.

Table 2.4. Shoreline retreat (m) under different SLR scenarios in 2050, 2075, and 2100. The values are referenced to 2015 measurements.

Coastal comarcas	Shoreline retreat (m)			
	SLR scenario	**2050**	**2075**	**2100**
1, 2, 3	RCP 4.5	15	28	41
	RCP 8.5	17	35	59
	H+	35	81	147
4, 5	RCP 4.5	13	24	35
	RCP 8.5	14	30	51
	H+	30	70	126
6, 7, 8, 9, 10	RCP 4.5	17	32	47
	RCP 8.5	19	41	68
	H+	40	93	168

2.4.2. Physical-Carrying Capacity (PCC)

At present, beaches along the coast can accommodate up to maximum of about 1.37 million users at one time (excluding the Ebro delta beaches). They present a non-homogeneous distribution per comarca that reflect the dominant geomorphology and extension of each unit.

The PCC distribution aggregated per tourism brand is shown in Table 2.5. As can be seen, the two most well-known Catalan tourism brands, Costa Brava in the north and Costa Dorada in the south, comprise about 60% of the total PCC, whereas they comprise 67% of the tourist bed places. The largest PCC is provided by the Costa de Barcelona brand, which includes the comarca with the highest number of users (272,000), Maresme, which is composed of a 42 km-long sandy coastline. In spite of being the brand with the largest PCC (34% of the total), it only provides 16% of total tourist accommodations. Finally, the city of Barcelona, the area with the highest tourist affluence, only supports 6% of the PCC.

PCC projections along the analysed coast show a decrease for all areas, although with significant spatial variation. Thus, considering the expected changes by 2050 under current conditions, the total PCC of the analysed beaches will decrease down to 81% of the current capacity (1,108 million users). Observed spatial variability is due to the combination of variations in coastline evolution and beach morphology. The least affected brand will be Costa Brava, which will maintain 89% of the present PCC (392,000 users in 2015, Table 2.5). This is due to its geomorphology characterized by bay beaches within headlands having relatively low erosion rates. On the other hand, Costa de Barcelona is the most affected tourism brand, where PCC decreases to 77% of the current capacity. This area includes the Maresme comarca, which has the largest shoreline erosion rates along the Catalan coast (excluding Ebro delta beaches).

The total PCC by 2050 under the RCP8.5 scenario will decrease to 64% of the present capacity (880,000 users, Table 2.5). Although this value is similar to that predicted under the influence of current coastal processes, the observed spatial variability is quite different, with all zones presenting similar reduction rates. In comparison with the previous scenario, the Costa Brava will be one of the most affected brands, maintaining 68% of present PCC. On the other hand, the PCC of Maresme beaches will be reduced down to 54% of actual values, which represents a 10% increase with respect to current climatic conditions. For the other tested scenarios, PCC will also experience the same decreasing trend which is proportional to SLR. Thus, in 2050, the total PCC will be 916,000 users under RCP4.5 and 616,500 users under the H+ scenario. These reductions will significantly increase beyond 2050 due to the expected SLR acceleration under tested scenarios.

Table 2.5. Characteristics and PCC for the different tourism brands along the Catalan coast.

Tourism brand	Comarca	Beach length (km)	Tourist accommodation (bed places in thousands)	PCC - thousands of users – (percentage over total)		
				2015	2050	2050
				reference	current climate	RCP8.5
Costa Brava	1, 2, 3	54.33	179.44	392 (29%)	347 (31%)	267 (30%)
Costa de Barcelona	4, 6, 7	63.91	72.02	471 (34%)	363 (33%)	305 (35%)
Barcelona city	5	12.88	73.54	82 (6%)	64 (6%)	50 (6%)
Costa Dorada	8,9,10	57.34	112.54	421 (31%)	334 (30%)	257 (29%)
Total			**437.54**	**1,366**	**1,108**	**880**

2.4.3. Tourist *BCC*

Fig. 2.7 shows the BCC integrated at the municipality and comarca scales versus potential users (tourists). At present, when the tourist BCC is integrated at the municipal scale (Fig. 2.7a), beaches are able to absorb between 80-100% of the potential demand. There are three locations lacking sufficient space to accommodate the potential maximum demand: Santa Cristina d'Aro (Baix Empordà), Barcelona (Barcelonès) and Cubelles (Garraf), which only satisfy 17%, 59%, and 61% of the local demand, respectively. However, if the spatial integration is enlarged up to the comarca level, which implies that users can be redistributed to all beaches within a given comarca, all regions will satisfy the potential maximum tourist demand (Fig. 2.7b). It has to be considered that the change in the scale of the spatial aggregation will reflect the maximum distance to be covered by users to visit a beach from their place of lodging.

As expected, the percentage of tourism demand satisfied by beaches will decrease with time and with the magnitude of sea level rise. As an example, in 2050 and under current climate conditions, the number of municipalities with insufficient beach surface to support 100% of the tourist BCC will increase from 3 to 10. In fact, if no adaptation action is taken, some beaches will disappear and the expected tourist BCC for some municipalities will become nil (*e.g.,* Caldes d'Estrac and Cabrera de Mar in Maresme) (Fig. 2.7a). When the effect of different SLR scenarios is considered, the number of significantly-affected municipalities increases (Fig. 2.7a). Thus, for the RCP8.5 scenario, 10 municipalities will present low or very low tourist BCC, increasing to 23 under the H+ scenario. It should be noted that severely affected municipalities are different than those identified under current conditions, with most of them being located in the Costa Brava (Cadaqués, Palafrugell, and Blanes) (Fig. 2.7a). When the analysis is at the comarca level, the tourist BCC reduction is smoothed out due to the potential redistribution of beach users within a larger unit. La Selva is the only affected comarca with decreases to 40% of the current tourist under BCC RCP8.5 scenario (Fig. 2.7b).

When the analysis is extended to 2100, a dramatic decrease in tourist BCC is expected, especially for RCP8.5 and the H+ scenarios (Figs. 2.7a and b). Under the RCP8.5 scenario, the tourist BCC for about half of the coastal municipalities will decrease to less than 20% of present values (Fig. 2.7a). If values are integrated at the comarca level, a smaller effect on the tourist BCC is observed. However, some comarcas experience a significant reduction; with La Selva (Costa Brava) being most affected as it will only be able to provide 2% of the required tourist BCC in 2100. Other significantly affected areas are Baix Camp and Tarragona (Costa Dorada), which will be able to provide 48% and 78% of the required BCC, respectively, and Barcelonès (city of Barcelona) and Baix Empordá (Costa Brava) with 38% and 19%, respectively (Fig. 2.7b).

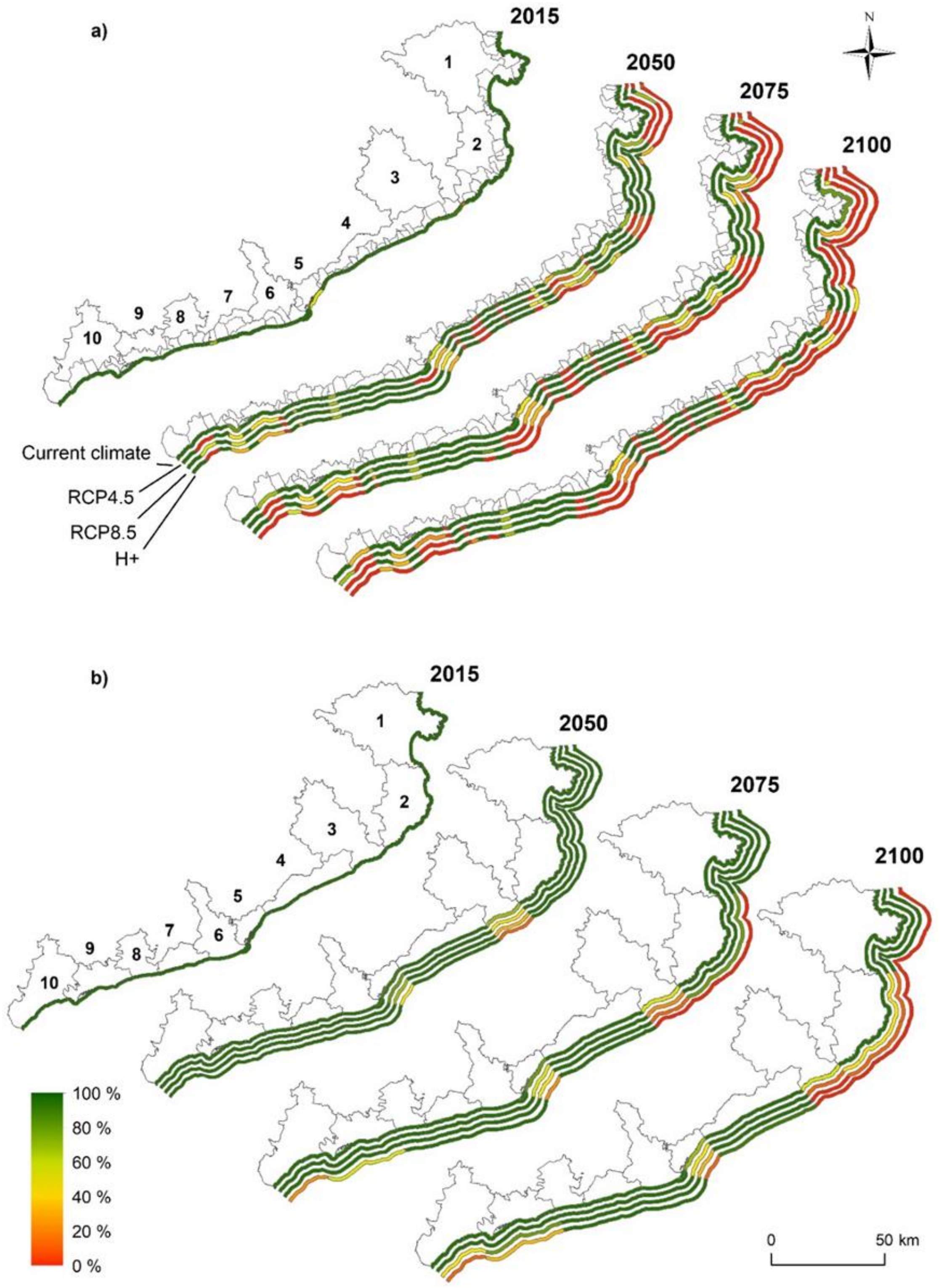


Figure 2.7. Tourist BCC integrated at the (a) municipal level, and (b) comarca level.

2.5. Discussion and conclusions

2.5.1. Methodological aspects

A methodology to assess the evolution of the recreational capacity of beaches at different management scales as a function of coastline evolution is proposed and applied to Catalan beaches under different climate scenarios. In this sense, this research belongs to the category of quantitative approaches to evaluating the effects of climate change on tourism based on a consideration of physical changes (Roselló-Nadal, 2014). Most existing analyses on the potential effects of climate change on sustainability of coastal tourist destinations focus on potential changes in climatic attractiveness (e.g., Amelung and Viner, 2006; Moreno and Amelung, 2009b; Perry, 2006, among others). However, in addition to climate conditions, beaches are the main resource for sustaining tourism in most coastal destinations, such as the Mediterranean countries, and any impact on the quantity and quality of beaches will affect tourism. In a business scenario in which the success of every season is usually indicated in terms of the percentage of increase in incoming tourists, any sustainable long-term planning requires an assessment of the evolution of the main resource to be "exploited", the beach. In this context, the evolution of the available beach surface area will determine the potential maximum number of users that can be served as well as the user density, the latter aspect being an important issue in influencing the user perception of beach quality (e.g., Ariza et al., 2010; Roca et al., 2008; Rodella et al., 2017).

With respect to this, Valdemoro and Jiménez (2016) among others have formalized the relationship between shoreline dynamics and beach user density. Thus, the inclusion of long-term erosion rates emerges as a key factor to estimate future beach carrying capacity under current conditions (*i.e.*, Alexandrakis et al., 2015; Rodella et al., 2017; Silva et al., 2007; Zacarias et al., 2011). On the other hand, climate change projections have determined the need to assess SLR-induced changes in carrying capacity (e.g., de Sousa et al., 2018; Jiménez et al., 2017; Scott et al., 2012b; Toimil et al., 2018). In this work, we have compared the contribution of each component of shoreline evolution to future carrying capacity variations and, have combined both to assess their integrated effect. This is important since when designing management responses to this future threat, such as nourishment volumes to maintain beaches (e.g., Hinkel et al., 2013), we have also to consider needs under current conditions which will have to be added to the so-estimated volumes to assess the existence of enough resources (e.g., Jiménez et al., 2011; 2017).

While SLR-induced erosion is an indisputable hazard to be included in any long-term assessment, there is much less agreement on how to properly assess it. Thus, in spite that the Bruun rule is probably the most used methods to predict shoreline retreat (e.g. Le Cozannet et al., 2014), there is a disagreement about its validity (see e.g., Cooper and Pilkey, 2004). In consequence, there have been different attempts to modify, reformulate or propose new models (e.g., Ranashinge et al., 2012; Rosati et al., 2013; Taborda and Ribeiro, 2015). However, these models also present the same shortcoming than the Bruun rule, *i.e.* they have been hardly verified and/or validated and, in this sense, they also have an inherent uncertainty. One of the problems to select a reliable method is the lack of adequate data for validation due to the hypothesis done by models and, in consequence, the limitation of existing data fulfilling such conditions (see e.g., Le Cozannet et al., 2016; Zhang et al., 2004). Recently, some works have addressed model validation using laboratory experiments (e.g., Atkinson et al., 2018; Beuzen et al., 2018; Monioudi et al., 2017), although still they are limited in quantity and need to be completed to perform a robust validation of existing models. Within this context in which no universally accepted model exists, we have selected to use the Bruun rule to estimate SLR-induced shoreline retreat. To this end, we have applied it by following recommendations of Stive et al. (2009) who suggested using it for regional scale assessments. In this sense, we do not apply the model at the beach scale, but we use to obtain regional scale SLR-induced background erosion. In this case, as we mentioned in the methodology section, we have divided the Catalan coast in three zones in terms of the inner shelf slope and we obtain a representative background erosion rate for each zone. This rate is later applied to each beach, with the corresponding time-response being the combination of such regional erosion rate and the local beach width. It has to be also noted that here we are assuming that no changes in sediment sources/sinks along the coast are considered (see e.g., Jiménez et al., 2017).

In this study we assume a model of use of the beach space and defined maximum-use density values, based on local characteristics. Both elements can be modified to adapt to sites with different spatial distribution of users or, to test how BCC would vary under different management scenarios, such as accepting a higher density of users. Therefore, this simple, flexible, and easy-to-use beach-user interaction model can be adapted to physical changes as well as to modifications in the beach management model.

One of the advantages of the adopted approach is that we have defined a model of use of the beach space, including saturation density values based on local characteristics. Therefore, each beach is classified in terms of its current use characteristics and, thus, the SLR-induced beach width decrease will have a differentiated impact on BCC. This approach permits to assess the impact on regional BCC by changing local beach management, as it would be the case of modifying accepted saturation levels. In our case study, we have assigned different intensity of use and saturation levels values using existing databases where all beaches were previously classified in terms of these two variables. In the case of non-existence of such information, the same procedure could be applied by assigning different saturation values as a function of their typology (e.g., urban, semiurban, natural).

One of the management-oriented key points of the model is the spatial integration of the BCC. The adopted approach integrates the carrying capacity from a basic unit, the beach, up to a given spatial (management-oriented) unit such as the municipality. This model assumes that the maximum level of mobility of tourists is determined by the integration scale, in such a way that beaches within a given management unit are only serving tourists staying in such unit. This has two main implications: (i) first, from the managerial standpoint, BCC is assessed as an integrated variable accounting for all beaches within a given management (integration) unit; and (ii) second, the implicit consequence is that if all beaches within a given unit lack of sufficient carrying capacity, tourists will change their destination, *i.e.,* they will move on to a different municipality or brand providing sufficient BCC. In this sense, the developed methodology allows assessing the capacity to accommodate the maximum potential number of tourists in the territory by redistributing the demand over different spatial units. This should facilitate exploring the formulation of adaptation measures based on the management of the accommodation offer along the territory taking into account the spatial distribution of future BCCs.

The tourist sector is here indicated by means of the maximum number of potential visitors derived from the total number of tourist bed places. However, it has to be considered that this number does not include people using accommodations that are not reflected in official statistics, such as accommodation-sharing sites, second-home residences, or day-visitors from outside the management unit. As an indicator of the potential capacity associated with this "uncontrolled" component, the report on the 2017 summer tourist balance in Catalonia (Generalitat de Catalunya, 2017) estimates that the housing for the tourist-use component offers about 35% of total bed places. This implies a "best-case scenario" impact assessment, since the maximum potential total tourist demand would be larger than that considered here. The use of bed places to compare with the BCC implies the assumption of full occupancy. To put into context the obtained results, the above-mentioned report (Generalitat de Catalunya, 2017) stated that the occupation rate during the 2017 summer season (June to September) in hotels in the analysed coastal tourism brands was about 83%. In the analysis presented here we have assumed that the offer of tourist accommodations within a spatial unit will not change with time. This is not a requirement of the model, which can be modified to take into account any time variation in the beach demand, including scenarios of growing tourism sector.

2.5.2. Temporal and spatial changes in *BCC*

The results indicate that at *present*, beaches along the Catalan coast (excluding the southernmost comarcas comprising the Ebro delta) can accommodate a maximum of about 1,366 million beachgoers under the current model of use (use of the available space and maximum allowable user density for each beach). This overall capacity is larger than the total number of tourist bed places and it should indicate that at present, Catalan beaches have the capacity to accommodate the maximum potential tourist demand. However, if we impose a limitation in tourist mobility, which is here modelled through the spatial integration of BCC, to the municipality scale, beaches along the Catalan coast are able to accommodate up to 89% of the maximum potential tourist demand without changing current beach management. Barcelona is one of the most affected municipalities, with beaches providing 59% of its tourist BCC due to the large number of tourists. However, this quantity of tourists is not directly linked to beaches since Barcelona is not the classical sun-and-sand destination. To put the obtained results in context, according to the Barcelona municipality, the influx of users to Barcelona beaches during 2016 was about 4.7 million, and the average used surface per visitant was estimated in about 7 m^2/user, with some beaches having values lower than 4 m^2/user (Ajuntament de Barcelona, 2017). In any case, it should be considered that the degree of occupation of these beaches presents significant time variations such that the same beach can range from situations of low occupation to saturation (e.g., Guillén et al., 2008). In order to properly interpret overall results, it has to be considered that at present, there are municipalities along the Catalan coast which are able to support 100% of the current tourist demand, which at the same time, present singular user density values close to or above saturation levels at some beaches (e.g., Roca et al., 2008; Sardá et al., 2009).

As it was already mentioned, beach width projection under current conditions have been estimated assuming that current natural and management conditions will not vary during the projection time. Thus, any potential change in current shoreline management options should affect future shoreline evolution and BCC even assuming no change in climate conditions. To assess the potential magnitude of such changes, if current maintenance beach nourishments performed during the last years, this would imply an increase of -0.1 m/y in the average background shoreline retreat rate.

Projection of present shoreline trends along the Catalan coast to 2050 indicates a 19% decrease in the overall PCC under current dynamic conditions, which would increase under a highly-probable climate change due to the estimated SLR-induced erosion up to 33%, 36%, and 55% for RCP4.5, RCP8.5 and H+ scenarios, respectively. When these figures are put in the context of potential implications for tourism, even in the absence of climate change, some municipalities will experience a measureable decrease in tourist BCC such that beaches will only be able to accommodate 83% of the maximum potential tourist demand if no actions are taken to manage them. Future tourist BCC perspectives will be much worse for the case in which climate change-induced effects are considered, with the capacity to absorb the maximum potential tourist demand being 74%, 72%, and 53% for RCP4.5, RCP8.5 and H+ scenarios, respectively. It should be considered that this decrease in tourist BCC is not evenly-distributed along the Catalan coast. It is mainly concentrated in municipalities in the North (Costa Brava), where the number of potential tourists is very high and beaches are relatively narrow (Fig. 2.7a).

For longer-term projections, this behaviour is reinforced and extended along the entire Catalan coast. Thus, for instance, under the RCP8.5 scenario, the overall tourist BCC will be 51% and 34% of the current maximum potential tourist demand in 2075 and 2100, respectively (Fig. 2.7a).

However, if we increase the aggregation scale up to the comarca level, the excess of users above saturation levels is redistributed among all beaches within a larger spatial unit. This indicates that the coastal system has the capacity to better absorb the overall demand (Fig. 2.7b) following a redistribution of users across the territory. It should be noted that the scales of aggregation have been selected in accordance with the administration structure in Spain, but since the information is individually obtained for each beach, the integration can be carried out at any spatial scale. As a rule of thumb, results show an increasing number of tourist BCC hotspots as the territorial unit becomes smaller. Consequently, this analysis between different integration scales could be useful in order to define more optimum management scales, and to locate hotspots and priority areas in order to define an adaptation strategy focused on sustaining the recreational use of beaches.

Regarding the tourist BCC hotspots identified here, the results indicate that the expected capacity to absorb the tourist demand of beach space of a given quality will be significantly affected by climate change if measures to avoid the BCC loss are not adopted. One of the most potentially-affected brands will be the city of Barcelona, although from the standpoint of tourism, this destination has other multiple tourist attractions, such as culture, architecture, and gastronomy. Regarding the most well-known coastal tourism brands, Costa Brava and Costa Dorada, both have municipalities that would be severely affected over long-time scenarios (to 2100), losing 87% and 53% of their current tourist BCC, respectively under RCP8.5.

Although beaches are used by both tourists and the local population, here we have focused exclusively on the tourist sector. In this sense, the estimated impact would be a “best-case scenario,” because if we also account for the use of beaches by the local population, the available surface will be further reduced. In this sense, data on beachgoer’s origin obtained in different beaches in the Costa Brava area indicate a percentage of locals of about 20-30% (Lozoya et al., 2014; Roca et al., 2008). This percentage of beach use by locals would increase in areas with low tourism and high population density, such as Maresme south, the metropolitan coast northwards of Barcelona (Ballesteros et al., 2018). To get an order of magnitude of this effect, assuming that on average, 25% of beach users are of local origin, the overall tourist BCC integrated at the municipal scale for the area of study under RCP8.5 scenario will be 65%, 45%, and 31% of the current maximum potential tourist demand in 2050, 2075, and 2100, respectively.

The results show the high sensitivity of the coastal tourism sector to climate change not only as a function of the change in climatic conditions controlling comfort, but in terms of time variations in the primary resource to be exploited, *i.e.*, the beach. The assessment presented has been done for a scenario of constant-over-time tourist accommodation capacity and consequently, constant potential beach demand by tourists. In this sense, this can be considered a best-case scenario which could be refined by testing different scenarios of time-evolution of tourists, including government aspirations for the tourist industry.

2.5.3. Management implications

In all cases, these results indicate that to maintain the economic contribution of the tourist sector, efficient adaptation measures are required. The aim of these measures should be to maintain future beach carrying capacity within a given range in order to properly support beach demand. This could be done or by (1) redistributing users along the coast, (2) increasing the density of use, (3) increasing the beach surface, or (4) combining some of them. Regarding the option 1, this strategy would not likely be implemented at a regional scale, since it implies “abandoning” well-established areas with local economies strongly linked to tourism (e.g., Costa Brava). However, from a local standpoint, this could be an opportunity for less-developed areas, which could offer new accommodation units in areas with enough BCC. Option 2 would imply a decrease in beach quality with the corresponding effects on users. Since many of the beaches analysed here are urban ones in which the accepted saturation level is high, the increase in density for these beaches would lead to a situation of permanent overcrowding. In the remaining beaches, the increase in user density implies that in effective terms, they will change from semi-urban and natural beaches to urban-like ones. Finally, the management of BCC through the conservation of available beach surface requires the implementation of traditional, coastal engineering measures to reduce and/or to compensate erosion. Along the Catalan coast, this has been the traditional way of mitigating erosion problems, such that during the last 30 years, more than 25 million m^3 of sand nourishment have been deposited on Catalan beaches (e.g., Jiménez and Valdemoro, 2019). In spite of this nourishment strategy, Catalan beaches present an erosive behaviour, which will be exacerbated under SLR. Consequently, the implementation of an adaptation strategy based exclusively on beach nourishment requires having a strategic sediment reservoir with enough quality sediment to maintain future beach widths. However, current estimates of existing nearshore sediment stocks are insufficient to cover expected needs (e.g., Galofré et al., 2018) unless new sand stocks are found. A possible approach to overcoming this limitation in existing resources will be to concentrate adaptation measures in high-priority areas identified with this analysis, where future beach evolution will result in a significant decrease in tourist BCC.

Chapter 3

Valuating the impacts of sea-level rise on the recreational function

3.1. Introduction

In the previous Chapter, the physical impact of SLR has been assessed in terms of reduction in the physical carrying capacity (PCC) of beaches along the Catalan coast, which should directly affect the tourism industry. Given the economic importance of this sector on the national GDP, here we assess the economic dimension of the estimated impacts under different SLR scenarios.

There are several methods to evaluate in economic terms the recreational value of beaches, such as travel cost (TC), hedonic pricing (HP), and contingent valuation (CV). TC involves accounting for costs incurred by beachgoers in traveling to the recreational site (Bell and Leeworthy, 1990; Fleming and Cook, 2008). HP identifies the factors and characteristics that affect an item´s price, such as the value of beach width (Pompe and Rinehart, 1995) or beach recreation (Edwards and Gable, 1991) capitalized in property values. Finally, CV estimates the value that a person places on beaches asking their willingness-to-pay (WTP) to obtain a specific service or function (Shivlani et al., 2003; Whitehead et al., 2008). However, these methods respond to users' prices attributable to a beach and do not reflect its real value since obtained non-market values (i) are highly dependent on user preferences and local characteristics; and (ii) do not provide an integrated valuation required to manage properly coastal resources (Ariza et al., 2012).

Although there is vast literature on beach quality assessment from the recreational standpoint (Ariza et al., 2012; Pendleton et al., 2001; Roca et al., 2009), less attention has given to quantitatively assess the direct economic impact of beach recreation. It is well-recognized that beaches play an important role as locations for recreation and, indeed, a key element for the tourism industry (Houston, 2013) in such a way coastal tourism comprises the largest market segment of this sector worldwide (Hall, 2001; UNEP, 2009b). In fact, King and Symes (2003) suggested that the US economy would lose \$2.4 billion in GDP annually if beaches were unavailable for recreation due to reductions in beach width and associated carrying capacity. More recently, Alexandrakis et al. (2015) estimated the value of eroded beaches in Greece by tourism revenue losses which, on average, were roughly €50 thousand/m^2 per year after 10 years of shoreline retreat. For the Catalan coast, Ariza et al. (2012) assessed the value of beaches in highly touristy areas which was estimated at approximately €7 M/ha in the peak of summer, a much higher value than other coastal areas (e.g. Edwards and Gable, 1991; Kline and Swallow, 1998; Silberman et al., 1992; Taylor and Smith, 2000).

According to the UN' World Tourism Organization, the total contribution of tourism in 2019 was 10.3% of global GDP generating 1 in each 10 jobs around the world (UNWTO, 2020). Furthermore, this institution has developed methodologies for evaluating the economic impact of tourism in the form of Tourist Satellite Accounts (TSA) based on input/output (IO) Tables. IO analysis measures the activity of producers and purchases of goods and services across the spectrum of economic sectors (Vellas, 2011), and it is one of the best methodologies to demonstrate how economic sectors are interlinked (Briassoulis, 1991; Fletcher, 1989; Sun, 2007).

Tourism is one of the most sensitive economic sector to climate change. Although potential impacts have been addressed (Priego et al., 2015; Rutty and Scott, 2014), economic consequences on coastal tourism have not been explored in detail so far (Amelung et al., 2008). Climate change may trigger a crisis in the tourism industry at many destinations in such a way is vital to understand the impacts and consequences for sustainable development of this sector (de Sausmarez, 2007; Meheux and Parker, 2006) as well as to consider different adaptation measures (Moreno and Becken, 2009, Scott et al., 2012). In this sense, Kirezci et al. (2020) suggested that SLR-induced flooding may threaten up to 20% of global GDP by 2100, with much of it belongs to the tourism industry.

Within the Mediterranean, Spain is a traditional sun-and-sand destination where approximately 12% of the national economy comes from tourism (INE, 2019).

Particularly, for the Catalan coast, beaches are recognized as the main resource for the development of this sector (Rigall-i-Torrent et al., 2011). However, given the predicted decrease in the available surface of beaches due to SLR (López-Dóriga et al., 2019), the remaining question is how the economy will be impacted? To this end, we have estimated potential economic losses through IO analysis by assuming that beach PCC is linked to the potential tourism demand and, consequently, to the tourism consumption and output.

Within this context, the main aim of this Chapter is to assess the potential impact of SLR on the economic contribution of tourism. This is accomplished via two objectives: (1) application of IO analysis and downscaling to *comarca* level, the minimum administrative unit with available economic data disaggregated into sectors; and (2) assessment of the economic consequences of the reduction of beach carrying capacity under given SLR scenarios.

3.2. Data and Methods

3.2.1. General methodological framework

As it has been mentioned previously, beaches are the most important asset for coastal tourism development. However, to what extent the economy of a given area will be affected by the reduction of the number of potential beachgoers? To answer this question, a methodological framework consisting of four steps has been designed (Fig. 3.1): (i) assessment of the tourism expenditure; (ii) application of IO model to measure the economic impact by changes in tourism expenditure; (iii) regionalization of the economic impact to assess the effect on a given administrative unit; and (iv) assessment of the SLR-effect as a function of changes in the PCC.

It is assumed that, in coastal comarcas, most of the tourism is associated with the sun-and-beach model. In addition to this, the main hypothesis it that (coastal) tourism economy is proportional to the available beach carrying capacity, which would control the number of potential visitors as well as the quality of the beach destiny. With this, any change in the available beach surface in a given territory, can be translated to changes in GDP and employment.

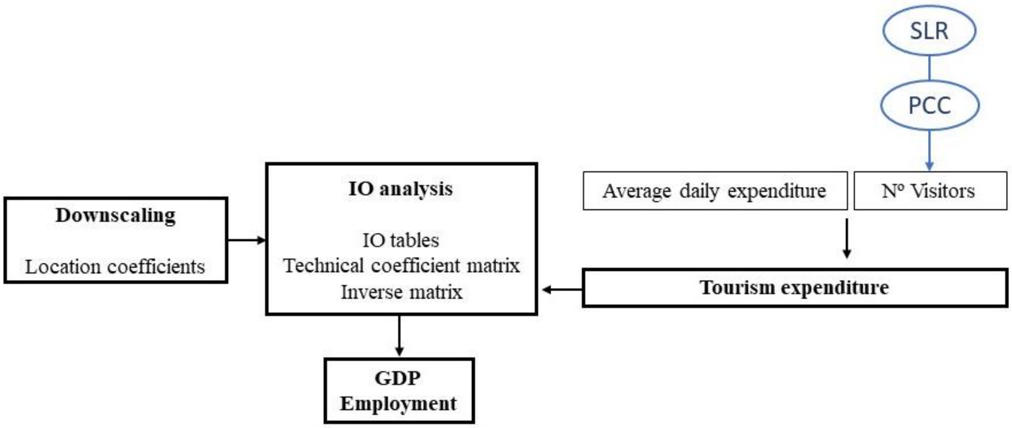


Fig. 3.1. Methodological framework to assess SLR-impact on the economy.

Tourism does not appear as a specific productive sector in the economic sphere. This is due to the fact that tourism is not defined by the goods and services it produces, which are not specific for the sector, but it is determined by the consumers' characteristics whose purchases are limited to the temporary visit of a territory. Such transversal character includes different economic branches, such as catering, commerce, transport, among others (Baró, 2003), with multiple businesses and companies participating in offering goods and services to tourists and, also, to the local population. All this means that, in order to evaluate the tourism contribution to the economy of a given territory, it is necessary to characterize the habits of tourists' expenditure and, from them, estimating the direct and indirect effects they generate.

Like any other economic activity, tourism can be analysed from the perspective of the demand and the offer. From the *demand perspective*, the economic value of tourism is calculated from the set of activities performed by tourists and the associated expenditure. From these consumptions, the generated effects on the local productive sector can be estimated. Conversely, the *offer perspective* considers the provision of tangible (products) and intangible goods (services) for tourist use. However, the key question is to determine which activities produce these goods, and which proportion can be directly associated with tourism, since local population also contributes to its consumption. For the objectives of this work, the most appropriate method to quantify the tourism impact is the demand point-of-view, which captures more accurately the consequences of tourism expenditure on the economy.

3.2.2. Assessment of tourism expenditure

3.2.2.1. Number of stays

Tourism demand in the study area is diverse, and following statistical data three typologies have been considered: (i) tourist, (ii) one-day visitor, (iii) second residence.

Data used to characterize the number of tourist overnights were acquired from official statistics provided by the Statistical Institute of Catalonia (IDESCAT). The selected indicators were the number of travellers and overnights by tourism brands (see Fig. 2.1 in the previous Chapter). Then, they were disaggregated down to the comarca-scale based on the number of tourist places within the tourism brand. The considering types of accommodations include hotels, campsites, cottages, as well as other unregulated lodgings such as *Airbnb* and other rental platforms.

To characterize tourists who do not overnight, one-day visitors' estimations made by the Barcelona Council (DIBA, 2020) obtained through surveys in certain municipalities have been used. From these, an average ratio with respect to overnight stays was calculated, and then applied to all coastal comarcas.

In order to define the demand from people having a second residence, data from the 2011 census (IDESCAT) were used, which were updated according to statistics related to housing and population inhabitants. To estimate the number of overnights in second homes, an average occupation of 2.82 people/home is assumed, which is the average value for the principal residence in Catalonia, and a stay of 90 days/year.

Table A2 in Annex A provides estimations about the number of stays per coastal comarcas in 2019.

3.2.2.2. Average daily expenditure

Data to calculate the average daily expenditure for each type of visitor were obtained from different statistic resources. Tourism expenditure surveys done by the Spanish Ministry of Industry, Commerce and Tourism (Egatur, 2019) and the Tourist Activity

Index developed by the Autonomic University of Barcelona (Duro, 2014) provide information on the expenditure made at the destination by tourists arriving to Catalonia, differentiating among different factors such as origin, mean of transport, type of accommodation, among others. Likewise, data from INE (2020a) allows for differentiating the expenditure made per tourism brand. These sources offer differentiated spending figures between the type of accommodation (hotels, campsites and cottages). The average expenditure per comarca has been obtained by Eq. 3.1,

$$GP = \frac{(GH * PH) + (GC * PC) + (GR * PR)}{P} \tag{3.1}$$

where GP is the average tourist expenditure per overnight, GH is the average daily expenditure of those staying in hotels, PH is the number of overnights in hotels, and GC, PC, GR, PR stand for same variables for campsites and rural cottages, respectively. Table A3 in Annex A shows obtained values for coastal comarcas, with an average value of 128.3 €/person·day.

The average expenditure of one-day visitors has been calculated by using data from INE (2020a) and Tourism Laboratory of the Barcelona Council (DIBA, 2020). Table A3 in Annex A shows obtained values for each coastal comarca, with an average value of 44.9 €/person·day.

Finally, to estimate the expenditure made by second homes, the level of expenditure per inhabitants in Catalonia and consumption patterns was analysed (INE, 2020b). Table A3 in Annex A shows obtained values for each coastal comarca, with an average value of 36.8 €/person·day. This figure does not include any component related to the home's construction and maintenance since the intention is to be the most restrictive with the concept of tourism expenditure.

3.2.2.3. Tourism expenditure

The total tourism expenditure per each coastal comarca (GT_c) is obtained by applying the Eq. 3.2,

$$GT_c = (Gt_C * Nt_c) + (Gv_c * Nv_c) + (Gr_c * Nr_c) \tag{3.2}$$

where Gt_C is the daily average expenditure per tourist overnights in comarca c, Nt_c is the number of tourist overnight stays in comarca c, and Gv_c, Nv_c, Gr_c, Nr_c stand for the same reason but for one-day visitors and second residences, respectively. Table A4 in Annex A shows obtained values for each coastal comarca.

3.2.3. Input-output model

3.2.3.1. IO Tables

Input-Output (IO) analysis is a quantitative top-down technique that represents the existing interdependencies between different sectors or industries. Originally developed by Leontief (1936), this model is commonly used for estimating the impacts (positive or negative) of economic shocks and analysing the domino effect throughout the entire economy (Miller and Blair, 2009). In particular, this work analyses the impact of tourism sector thought the tourism expenditure and its repercussions on the economic magnitudes of a given area, mainly income and employment. A very general and simplified overview of an IO Table is presented in Table 3.1, which is comprised by three sub-matrixes:

Quadrant 1 (intermediate transactions) is the basis for the IO model itself, and it includes the matrix of intermediate flows. It represents the transactions for intermediate sales and purchases of goods and services among sectors, i.e. inputs and outputs for each branch. Depending on whether a supply of demand approach is desired, it is analysed by rows or by columns. *Rows* represent the production (either in monetary terms or as coefficients) of each productive sector distributed by consumption sectors. *Columns* indicate the resources that each sector uses to produce the manufactured goods.

Quadrant II (final use) shows the final use of goods and services for each branch, which is composed by private consumptions (PC), public expenditure (PE), gross capital formation (GC) and exports (E). If intermediate consumption row (IC) is added to the corresponding final demand row (FD), the column vector of the total output (TO) is obtained, which is equal to the row vector of the total input (TI).

Quadrant III (primary inputs) contains the components which constitutes the added value (AV) of the corresponding branch and the surplus generated (SG). The input total (IT) is the sum of primary inputs and intermediate consumptions (IC).

Therefore, IO Table can be considered as an accounting instrument representing all economic activities grouped into activity branches and quantifying the transactions between them, the production that each one allocates to the final demand, and the use made of primary resources. Furthermore, IO Table constitutes a powerful simulation and forecasting tool allowing for an analysis of the induced effects by variations in the demand of a productive branch, in this case in tourism expenditure.

Table 3.1. General structure of an IO Table.

<table>
<tr><td></td><td></td><td colspan="4">Intermediate demand</td><td colspan="6">Final demand</td></tr>
<tr><td></td><td></td><td>Branch 1</td><td>Branch 2</td><td>Branch n</td><td>∑IC</td><td>PC</td><td>PE</td><td>GC</td><td>E</td><td>∑FD</td><td>TO</td></tr>
<tr><td rowspan="3">Intermediate input</td><td>Branch 1</td><td colspan="4" rowspan="3">Quadrant I
Intermediate transactions</td><td colspan="5" rowspan="3">Quadrant II
Final use</td><td>X_1</td></tr>
<tr><td>Branch 2</td><td>X_2</td></tr>
<tr><td>Branch n</td><td>X_n</td></tr>
<tr><td rowspan="2">Primary input</td><td>AV</td><td colspan="4" rowspan="2">Quadrant III
Primary inputs to production</td></tr>
<tr><td>SG</td></tr>
<tr><td>Total input</td><td>TI</td><td>X_1</td><td>X_2</td><td>X_n</td><td></td></tr>
</table>

3.2.3.2. IO analysis

The first step involved is the conversion of inter-branches transactions into a matrix showing the direct requirements of a sector to produce a unit of its product, called **the technical coefficients matrix or intermediate consumptions**. The technical coefficients are calculated from values taken from the *Quadrant I* divided by the total input of the corresponding branch (Eq. 3.3),

$$a_{ij} = \frac{x_{ij}}{X_j} \tag{3.3}$$

where x_{ij} is the amount of production input supplied by branch i used by the branch j to obtain its production X_j, i.e., the necessity of branch j in products of branch i to achieve an unit of good it produces.

The technical coefficient matrix provides a simplified vision of the existing technical production relationships between different branches of an economy. It is configured as a square-matrix of "n" rows and "n" columns indicating the number of branches into which the whole economic activity is disaggregated; in this case into 82 economic branches. Therefore, the technical coefficient matrix makes it possible to analyse the effects resulting from changes in the economic activity. These effects occur beyond the production branch in which the activity is increased, since one-unit increment in the final demand for products of a branch j will imply not only the provision of all intermediate inputs necessary to its production but also a whole chain of subsequent needs. In fact, an increase in the productive branch activity causes an increase in the input demand to develop such activity (Eq. 3.4),

$$X_1 = A \cdot D \tag{3.4}$$

where A is the technical coefficients matrix, D the increase demand vector and X_1 the supply needs to new inputs. However, this increase in production to satisfy the initial demand causes a new need for inputs to be produced (Eq. 3.5).

$$X_2 = A \cdot X_1 = A \cdot (A \cdot D) = A^2 \cdot D \tag{3.5}$$

This process will be repeated indefinitely since each new production requires new inputs to be supplied, although, logically, this sequence will have decreasing values. This iterative model allows us to capture easily and simply the sequence chain of inputs needs of the productive system represented by the sum of all its components as well as the increase in the initial demand (D) (Eq. 3.6).

$$X = D + A \cdot D + A^2 \cdot D + A^n \cdot D = [Y + A + A^2 + A^n] \cdot D = [Y - A]^{-1} \cdot D \tag{3.6}$$

Solving Eq. 3.6 for the total output, $[Y - A]^{-1}$ is the so-called Leontief inverse or demand multiplier showing the input supply needs resulting from a change in the activity of one or more productive branches.

The use of technical coefficient matrix and Leontief inverse matrix of IO Table allows us to convert expenditure and investment data into macroeconomic variables such as GDP and employment of each coastal comarca.

Three types of effects can be distinguished by applying IO model: (i) direct effects derived from the income received by the different productive factors as a consequence of the consumptions and expenses made by the different types of visitors; (ii) indirect effects caused by the increase in the economic activity related to tourism and the investment made in complementary activities; and (iii) induced effects generated by the increase in the economic activity associated to the expenses made by people directly or indirectly linked to tourism. The sum of these allows assessing the overall tourism impact in a given territory.

Finally, IO Tables differentiate economic fluxes within Catalonia, the rest of Spain, and relations with foreign countries, which allow us to know how GDP and generated work positions are distributed along the territory quantifying the effect of spillover. Such an effect is referred to as the fact that an action taken in a certain territory (investment or expenditure) affects the economy of another one. In the case of tourism, with a wide range of related goods and services, these spillover effects tend to be significant.

3.2.3.3. IO Tables for Catalonia

The creation of IO Tables is a complex and long process analysing information available about economic transactions between different productive sectors, as well as on production, sectoral exports, and domestic demand. Statistical Institutions of each country promoted the creation and development of IO Tables at national level at first, and then at regional scale as more statistical information become available. The main methodological problem is associated with the availability of economic information.

In the case of Catalonia, the first IO Tables were developed by the Barcelona Chamber of Commerce (Muns and Pujol, 1972; Parellada, 1992), and by Barcelona University (CEP, 1982). Afterward, the IDESCAT developed IO Tables for the years 2001, 2005, 2011 and 2014. The most comprehensive IO Framework corresponds to the year 2011 in terms of data used and development of both technical coefficient and inverse matrixes, with a disaggregation into 82 productive sectors. This IO Framework has been updated to 2014 although neither the symmetric tables nor the technical coefficient and inverse matrixes have been developed for this year, which are key instruments to quantify the impact on the economy.

In this work, 2011 IO Framework was updated to 2014 values by adjusting the two basic matrixes for IO analysis (technical coefficient and Leontief inverse matrix), a method broadly applied (Brand, 2012). This update was based on macroeconomic data on the evolution of production and business account samples from diverse sectors of the Catalan economy allowing for productive relationship adjustments among them.

3.2.4. Downscaling to coastal *comarcas*

In order to evaluate the effect on a smaller scale, it is necessary to apply regionalization techniques to IO Tables (Álvarez, 2001). The most used technique to downscale IO Tables is the application of location coefficients (Flegg et al., 1997, Flegg and Tohmo, 2011) by applying them to the national coefficient of the IO Table (Brand, 2012). In this work, the approach of Garola (2019) for the regionalisation of IO Tables has been adopted, which is given by

$$A_{ij}^{r} = A_{ij}^{N} * q_{ij} \tag{3.7}$$

where A_{ij}^{r} is the coefficient of the IO Table at comarca level; A_{ij}^{N} is the coefficient of the IO Table at regional scale (in this case, Catalonia); and q_{ij} is the developed location coefficients based on the existing economic information. In the case of Catalonia, economic macro magnitudes are available for comarcas and for large cities. These location coefficients represent the existing relationship in sectors' production between comarcas and Catalonia (Eq. 3.8) and, by definition, they are smaller than one reflecting that each comarca is part of a superior administrative unit.

$$q_i = \frac{\frac{X_i^c}{X^c}}{\frac{X_i^N}{X^N}} \tag{3.8}$$

where, X_i^c is the production of sector i and $X^c$is the total production in the comarca c; and $X_i^N$and X^N stand for the same reason but for regional scale (Catalonia).

These location coefficients enable us to create new technical coefficient and inverse Leontief matrixes that allows introducing the local impact and, thus, to assess which part of the generated economic impact associated to the tourist expenditure ends up affecting the economy at the comarca scale. By applying this tool, it is possible to capture the effects of tourist activity in a particular comarca to calculate GDP and work positions.

3.2.5. Assessment of SLR-effect on the economy

As mentioned before, the main hypothesis is that any variation in the beach carrying capacity will imply a loss in the number of potential beach users and, consequently, a proportional reduction in the incurred tourism expenditure. The SLR-impact on the PCC evaluated for each beach in Chapter 2 has been aggregated at the comarca scale to be used in this analysis (see Annex A, Table A5).

The impact of SLR on the tourism-related economy has estimated by 2050, 2075 and 2100 under considered SLR-scenarios. Although the use of long-term scenarios is common in physical-impact assessments, its application for forecasting economic impacts is not a straightforward task. In this work, this is simply done by considering the expected decrease in tourism expenditure with respect to the current economy. This assumption simplifies the assessment without making any hypothesis about economic developments at comarca level over the next 80 years.

3.3. Results

3.3.1. Tourism impact on the economy

Total tourism expenditure in coastal comarcas was approximately €16,933 M in 2019, with 64%, 20%, and 16% being supplied by tourists, one-day visitors and second residences, respectively (Annex A, Table A4). Among coastal comarcas, Barcelonès stands out reflecting the huge importance of the city of Barcelona as a tourist centre. It has to be noted that although Barcelona beaches are intensively used all the year around, they are not the main interest of tourists but the city itself. In this sense, the economic impact of SLR on Barcelona will be clearly overestimated.

It should be noted that these figures are derived from the expenditure generated by tourists from a comarca within that unit, which is a very restrictive criterion where each comarca is considered as a closed unit. Thus, although tourism expenditures in a given comarca generate indirect and induced productive activities in others areas, these links have not been considered.

Using tourism expenditures, tourism activities have generated approximately €12,655 M in 2019, which represents 10% of the total GDP of coastal comarcas. Furthermore, spillover impacts have been estimated at around €4,630 M, part of which affecting other comarcas. With respect to employment, the tourism impact can be estimated at more than 187,000 work positions, representing roughly 10% of the total employment in coastal comarcas. To properly interpret these results, it has to be considered that the model works in annual terms, whereas beach/coastal tourist activities have a strong seasonality character.

Fig. 3.2 shows the effect of tourism on the GDP of each comarca. As it can be seen, there is a significant variability, ranging from 4% in Baix Llobregat to 29% in Baix Empordà. In any case, this value must be interpreted with caution since it depends on the importance of tourism, and also on the existence of other activities. Thus, the high values obtained in Baix Empordà and Baix Penedès are reflecting their importance as highly specialized areas in tourism, combining both tourists and second homes. They correspond to Costa Brava and Costa Dorada, the most well-known coastal tourism brands in Catalonia.

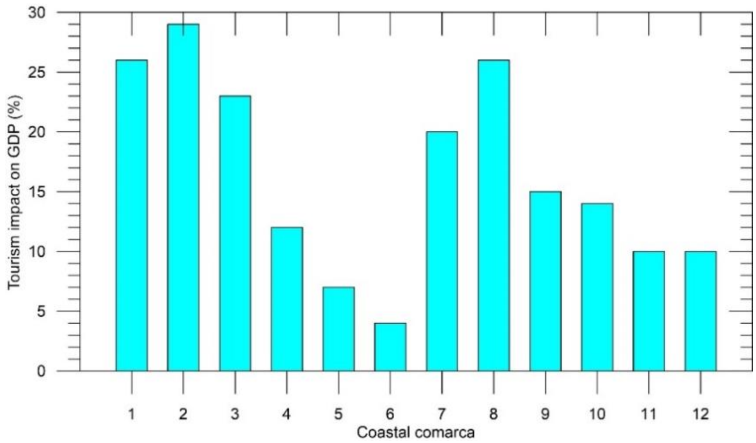


Figure 3.2. Tourism impact (in percentage over total GDP) for each coastal comarca in 2019 (from North to South: 1: Alt Empordà; 2: Baix Empordà; 3: Selva; 4: Maresme; 5: Barcelonès; 6: Baix Llobregat; 7: Garraf; 8: Baix Penedès; 9: Tarragonès; 10: Baix Camp; 11: Baix Ebre; 12: Montsià).

3.3.2. SLR-impact on the economy

Fig. 3.3 shows the impact of SLR on the tourism GDP of each coastal comarca with respect to 2019 values under different climatic scenarios. As expected, the percentage of the income associated with tourism will decrease with time and with the magnitude of SLR. In fact, the fall in tourism GDP will be very significant even without considering SLR due to the dominant erosive behaviour of Catalan beaches (Jiménez and Valdemoro, 2019). This is especially evident in Baix Ebre with an expected decrease in contribution to GDP ranging from 54% to 33% by 2050 to 2100, respectively. When the effect of SLR is considered, this contribution further decreases. As an example, comarcas within Costa Brava tourism brand may lose all their tourist activity under the most-extreme scenario due to the disappearance of their beaches.

Fig. 3.4 represents the quantification of this impact in monetary terms. Considering RCP8.5 as a reference, and without including Barcelonès (to avoid the before mentioned overestimation due to the weight of Barcelona city), the coastal comarcas of Baix Empordà, Selva and Tarragonès will suffer the largest reductions by losing more than €1,000 M on their tourism GDP by the end of the century.

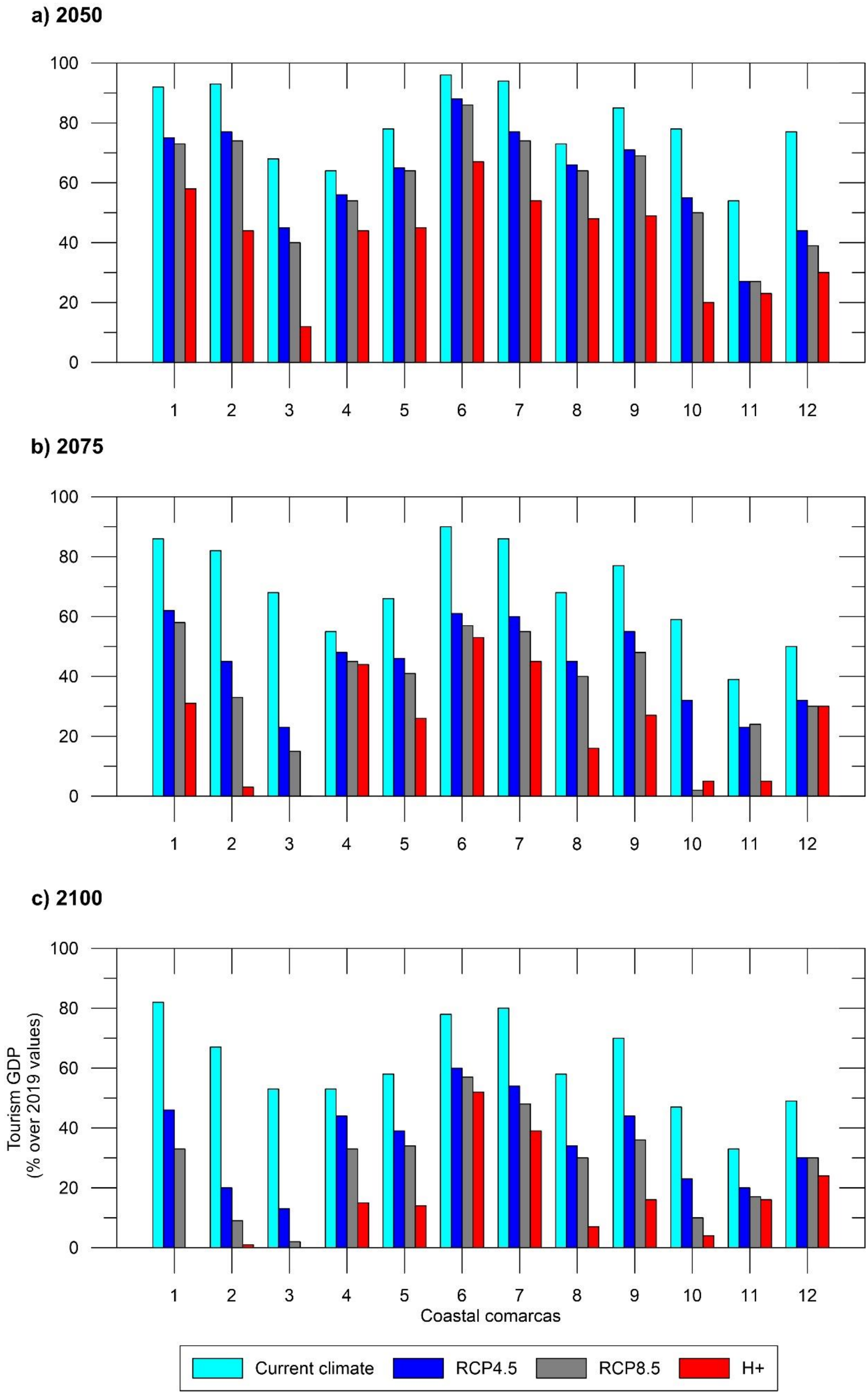


Figure 3.3. Variation in tourism GDP (in %) with respect to 2019 values under different climatic scenarios at a) 2050; b) 2075; and c) 2100.

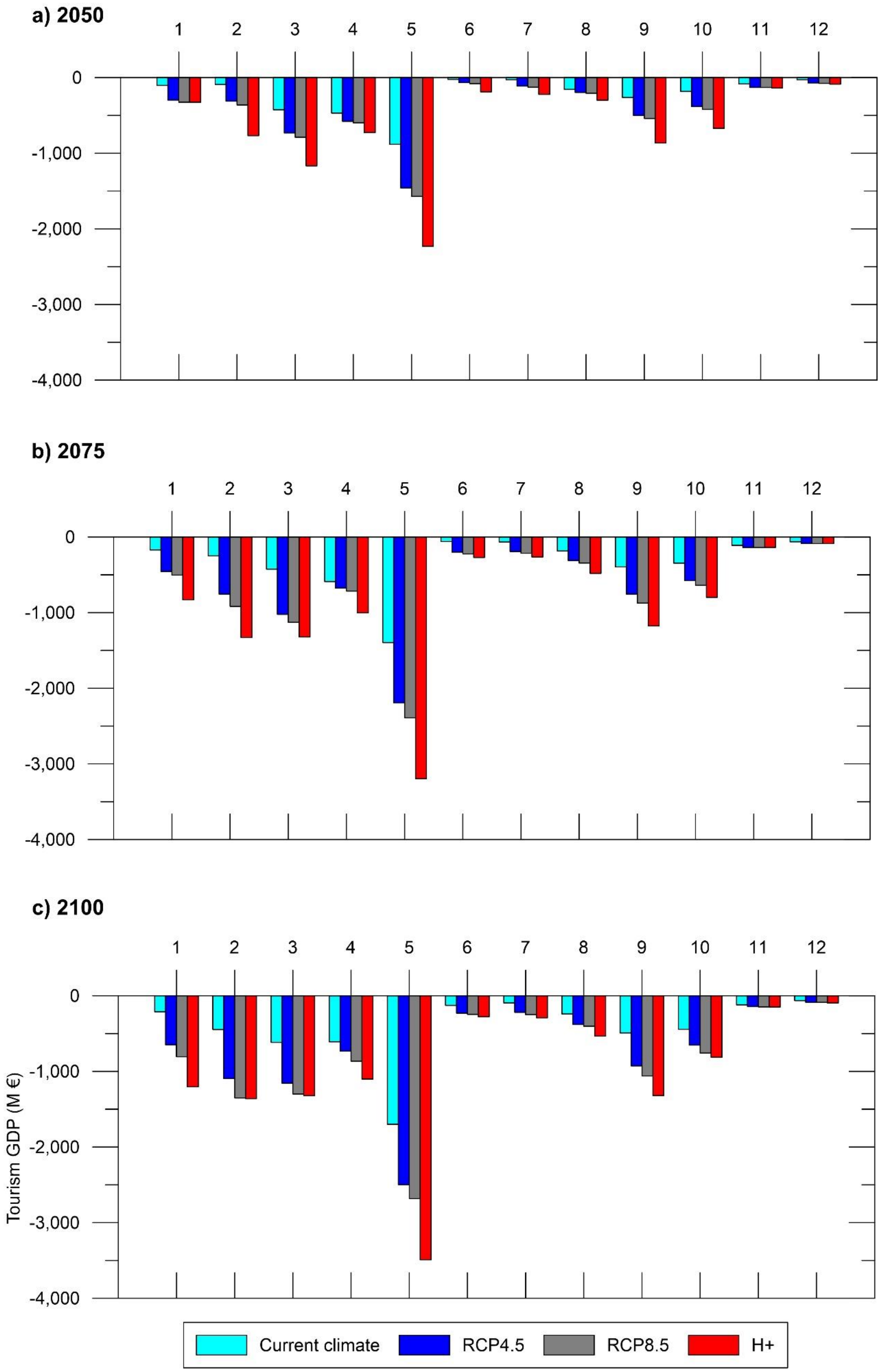


Figure 3.4. Reduction in tourism GDP (in M €) with respect to 2019 values under different climatic scenarios at a) 2050; b) 2075; and c) 2100.

Finally, Table 3.2 shows the effect of such reduction in tourism GDP on the total economy of each comarca. In general terms, the greatest lossess in GDP will occur in those highly tourism-specialized coastal comarcas. For long-term projections, the decline in GDP in Alt Empordà, Baix Empordà, Selva and Baix Penedès would exceed 20% under the most-extreme scenario (H+)

Table 3.2. Reduction in total GDP (in %) with respect to 2019 values for each coastal comarca under different climatic scenarios by 2050, 2075, and 2100.

	Scenario	Coastal comarcas											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
2050	EV	-2.2	-1.9	-7.3	-4.3	-1.6	-0.2	-1.2	-7.0	-2.3	-3.0	-4.8	-2.3
	RCP4.5 + EV	-6.3	-6.6	-12.5	-5.3	-2.6	-0.5	-4.7	-8.9	-4.4	-6.4	-7.4	-5.5
	RCP8.5 + EV	-6.9	-7.7	-13.4	-5.5	-2.8	-0.6	-5.3	-9.3	-4.8	-7.0	-7.5	-6.0
	H+ + EV	-10.8	-16.2	-19.9	-6.7	-3.9	-1.4	-9.3	-13.4	-7.9	-11.2	-7.9	-6.8
2075	EV	-3.6	-5.3	-7.3	-5.4	-2.5	-0.4	-2.8	-8.3	-3.6	-5.8	-6.3	-4.9
	RCP4.5 + EV	-9.7	-16.0	-17.5	-6.2	-3.9	-1.7	-8.0	-14.1	-6.9	-9.7	-7.9	-6.7
	RCP8.5 + EV	-10.7	-19.4	-19.2	-6.5	-4.2	-1.8	-9.0	-15.5	-8.1	-10.7	-7.9	-6.8
	H+ + EV	-17.7	-28.1	-22.5	-6.7	-5.3	-2.0	-11.1	-21.7	-11.2	-13.3	-8.5	-6.8
2100	EV	-4.5	-9.4	-10.5	-5.6	-3.0	-0.9	-3.9	-10.8	-4.6	-7.4	-6.9	-5.0
	RCP4.5 + EV	-13.8	-23.2	-19.7	-6.7	-4.4	-1.7	-9.2	-17.1	-8.6	-10.9	-8.2	-6.8
	RCP8.5 + EV	-17.1	-26.5	-22.2	-7.9	-4.7	-1.8	-10.4	-18.1	-9.9	-12.7	-8.5	-6.8
	H+ + EV	-25.6	-28.8	-22.5	-10.1	-6.2	-2.1	-12.2	-24.1	-12.9	-13.6	-8.6	-7.4

3.4. Discussion and conclusions

3.4.1. Methodological aspects

This Chapter investigates the economic contribution of tourism demand for coastal comarcas in Catalonia and the potential economic impact of SLR. It has been quantified through IO analysis the direct and indirect effects from tourist expenditures on the regional economy in terms of income and employment.

Main methodological constraints are associated with the inherent assumptions of the used IO methodology (Miller and Blair, 2009) as well as by the applied regionalization technique (Flegg and Tohmo, 2011). In any case, this has permitted to value beach tourism by using tangible economic data instead of using other approaches based on non-real expenditures as WTP-based methods.

Tourism's economic impact on a region is initiated by tourism expenditures. Due to this, the first data required is how much visitors spend on services and goods in the local economy (Frechtling and Horváth, 1999). Quantifying the tourism expenditure was a challenging task since it involves many aspects to consider such as (i) the proper definition of tourist-visitor concept, (ii) the hypothesis made about expenditure levels, and (iii) the application of models to obtain economic magnitudes from such expenses.

In this work we have assumed that the density of use of analysed beaches does not vary with time to do not change the user's profile of each location. By increasing the density of use in certain beaches, the carrying capacity could be maintained within a given range to support future demand. However, higher users' density scenarios would lead to overcrowding situations affecting the attractiveness of the area and, consequently, affecting the recreational use (Ariza et al., 2080; 2010). Therefore, this can be considered as the most plausible hypothesis apart from the unlimited number of possible scenarios that could be given for such long-terms projections. By this, a reduction in PCC would lead to a reduction in the number of users to maintain the density of use and, consequently, a reduction in tourism expenditure in the same proportion.

Finally, this work is restricted to the physical effect of climate change in terms of SLR. Other effects are also expected such as temperature increase, which are already important challenges faced by local authorities (March et al., 2014). In fact, most of the existing assessment of climate change on coastal tourism development focus on climatic attractiveness (e.g., Amelung and Viner, 2006; Moreno and Amelung, 2009b; Perry, 2006, among others). Therefore, the estimated impact on the economy will be higher than the presented here.

3.4.2. Economic consequences on recreational areas along the Catalan coast

Tourism activities in 2019 generated approximately €12,655 M in coastal comarcas of Catalonia, representing approximately 10% of the total GDP. These figures indicate that any variation in the development of this sector could have significant implications on the economy of a given area. Additionally, spillover effects must also be considered since, when tourists buy a product on a local shop or make a consumption in a restaurant, the economic impact is not limited to the territorial unit but also to the manufacturing area, which can be a remote area. This impact on the economy was quantified in terms of additional €4,630 M, but not territorially distributed. Therefore, the final contribution of tourism to GDP would exceed obtained values since they strictly reflects the impact of tourism expenditure in a comarca on itself.

Furthermore, the quantified effect here on the economy is not the only one. The predicted significant loss in work positions and generated activities would result in a loss of population affecting to other productive sectors (e.g., public services, administration) and, consequently, generating a greater economic impact. The use of this predictive model is an essential tool to design appropriate policies to each territory nor only to preserve tourism but also to generate alternative activities to compensate such reduction.

The economic impact of the SLR shows a high variability, reflecting differences in the vulnerability of the tourism sector between comarcas, a fact that should be taken when developing policies to cope with the effects of climate change. An adaptation measure will be economically viable if potential benefits are higher than the associated costs. If benefits were quantified in terms of avoiding losses in GDP, the comarcas where it will be more worthwhile to invest in adaptation would be Baix Empordà, Selva, Barcelonès and Tarragonès considering RCP8.5 as a reference (Table 3.3).

To sum up, the use of this type of predictive model is an essential tool to help coastal managers when designing proper policies for each territory both to preserve the tourism sector and to generate alternative activities that can compensate for its loss. This analysis reveals valuable insights on the effects of variations in beach users on tourism’s contribution to a regional economy.

Table 3.3. Potential losses in total GDP (in M €) at each comarca under RCP8.5 scenario if adaptation actions to maintain current PCC are not implemented.

Coastal comarca	2050	2075	2100
Alt Empordà	219	340	544
Baix Empordà	237	600	819
Selva	527	755	869
Maresme	405	485	587
Barcelonès	1,989	3,030	3,399
Baix Llobregat	126	387	387
Garraf	130	220	254
Baix Penedès	159	264	310
Tarragonès	393	661	814
Baix Camp	306	465	552
Baix Ebre	130	138	147
Montsià	82	94	94

Impact of sea-level rise on the natural function of the Catalan coast

Chapter 4

Impact of relative sea-level rise on low-lying coastal areas of Catalonia

Adapted from: López-Dóriga, U., Jiménez, J.A. 2020. Impact of Relative Sea-Level Rise on low-lying coastal areas of Catalonia, NW Mediterranean, Spain. Water, 12(11), 3252. doi: 10.3390/w12113252

4.1. Introduction

Sea-level rise (SLR) will significantly alter coastal landscapes through inundation, erosion and salt-water intrusion of low-lying areas worldwide. Considering that 10% of the world's population inhabits areas less than 10 m above sea level (McGranahan et al., 2007), the occupation of which has led to the widespread conversion of natural areas into economically productive regions (Valiela, 2006), the most dramatic and immediate effects of SLR will be the inundation of coastal lowland areas (Fitzgerald et al., 2008). In these areas, such as deltas, where accelerated rates of SLR are exacerbated by natural subsidence due to sediment compaction, inundation is likely by the end of the century (Syviski et al., 2009). Therefore, SLR coupled with subsidence rates (called relative sea-level rise, RSLR) will increase the vulnerability of coastal communities and economic sectors to flooding in the near future, causing both environmental and socioeconomic changes (Ericson et al., 2006; Nicholls et al., 2010).

Within this context, the Mediterranean coast is especially vulnerable due to the impact of RSLR due to the high concentration of sensitive low-lying areas, anthropogenic pressures, and natural hazards (Nicholls and Hoozemans, 1996; Reimann et al., 2018; UNEP 2009a). Moreover, impacts related to climate and environmental changes will be more severe than the expected global mean, with temperatures already reaching +1.5 °C above pre-industrial times (Cramer et al., 2018). As a consequence, there exists a large number of risk assessments to RSLR for low-lying environments in this region, such as for the Po delta and other Italian plains (Antoniolli et al., 2017; 2020; Bondesanf et al. 1995), the French Mediterranean coastline (Brunel et al., 2009), and the Egyptian coast (Frihy and El-Sayed, 2013) among others. Within this region, the Catalan coast can be considered a good example of the NW Mediterranean coastline, despite being largely urbanized, low-lying areas of high environmental value still exist (Brenner et al., 2008; 2010) that are highly vulnerable to SLR (e.g., Sánchez-Arcilla et al., 1998; 2008).

Generally, low-lying coasts are highly dynamic and ecologically and economically valuable systems. Due to their proximity to water bodies, coastal habitats are highly vulnerable to the impacts of SLR, meaning that determining their physical and ecological responses to future change is a difficult task. Although inundation is one of the most important SLR impacts on coastal zones, together with erosion and enhanced-storm induced flooding (Nicholls and Cazenave, 2010), there is a growing need to integrate dynamic interactions between physical and ecological factors to better predict the impacts of SLR on low-lying coasts (Passeri et al., 2015).

One of the most widely used method to assess SLR-induced inundation is the "bathtub" approach in which areas below a target water level and hydraulically connected to the sea are delineated as being flooded (Gallien et a., 2011; Poulter and Halpin, 2008). This method is suitable for armored, rocky, and passive coasts where the wave action is limited and the sedimentary supply is low (Leatherman, 1990). However, active sedimentary coasts have more dynamic effects than inundation alone, and processes driving coastal evolution are expected to occur as sea level rises (Fitzgerald et al., 2008; Gutierrez et al., 2009). In light of this, coastal fringes can be considered a natural barrier to counteract RSLR (Sánchez-Arcilla et al., 2008), and therefore, the dynamic responses of shorelines must be included in comprehensive assessments of future SLR-inundation, especially where the only form of protection is afforded from natural landforms such as beaches.

Another important challenge is relating the inundated area to the resulting damage. One approach is to consider the loss of function/habitat occupying the inundated area, e.g., Alvarado-Aguilar et al. (2012). However, this often overestimates damage, especially from an environmental standpoint, as the capacity of adaptation of natural areas is not considered (Kirwan et al., 2010; Lentz et al., 2016). Despite some uncertainty of how coastal habitats respond to changing conditions, considering the natural capacity of coastal areas to adapt to projected SLR is important for meaningful damage estimates (Van De Lageweg and Slangen, 2017). As an example, Lentz et al. (2016) found that 70% of the coastal landscape projected to experience future flooding has some capacity to respond dynamically to SLR, which significantly reshape the coastal landscape. Therefore, the use of static inundation models will likely overpredict the expected impact, leading to greater uncertainty for coastal managers. Therefore, to properly assess the impacts of future climate change, it is important to consider and quantify expected habitat changes (Bellard et al., 2012). As an example, the Sea Level Affecting Marsh Model (SLAMM) was specifically developed to characterize wetland resilience to SLR (Clough et al., 2016; Craft et al., 2009; Glick et al., 2013; Traill et al., 2011). This well-known model was broadly applied along the coast of the United States (Mcleod et al., 2010) but rarely adapted to microtidal areas, such as the Mediterranean coast (Prado et al., 2019). Quantifying the dynamic effects of SLR is also challenging because of the complex interactions between coastal processes acting at different temporal and spatial scales (Chu et al., 2014). In this study, we developed a simple Geographical Information System (GIS)-based methodology to assess the potential future damage to coastal habitats. Similar to the decision tree used in the SLAMM, we use transition/evolution rules to represent shifts between coastal habitats to obtain preliminary estimates of potential changes and associated damage from SLR inundation.

The two main aims of the study are to: (i) develop a method of assessing RSLR-related inundation of low-lying areas that accounts for dynamic coastal responses and (ii) apply the method to the low-lying areas along the Catalan coast in the NW Mediterranean, Spain. In doing so, we sought to shift the perspectives of coastal managers from considering RSLR solely as a threat to also considering it as an environmental opportunity. At the same time, we aimed to build on previous analyses on the impact of SLR-induced erosion along the Catalan coast (Jiménez et al., 2017; López-Dóriga et al., 2019). These previous studies show that, due to its topography and except for low-lying areas, the Catalan coast has a very low sensitivity to inundation (Ballesteros, 2017). Therefore, we focus on the most sensitive areas of the Catalan coast based on future SLR scenarios.

4.2. Study area and data

4.2.1. Study area

The Catalan coast is located in the northeast Mediterranean region, Spain (Fig. 4.1), and has an approximate coastline length of 600 km comprising cliffs, low-lying deltaic areas, and approximately 270 km of beaches. As of 2019, 63% of the total population in Catalonia (4.82 million people, IDESCAT) are concentrated in coastal comarcas (administrative units equivalent to a county), representing 23% of the total territory.

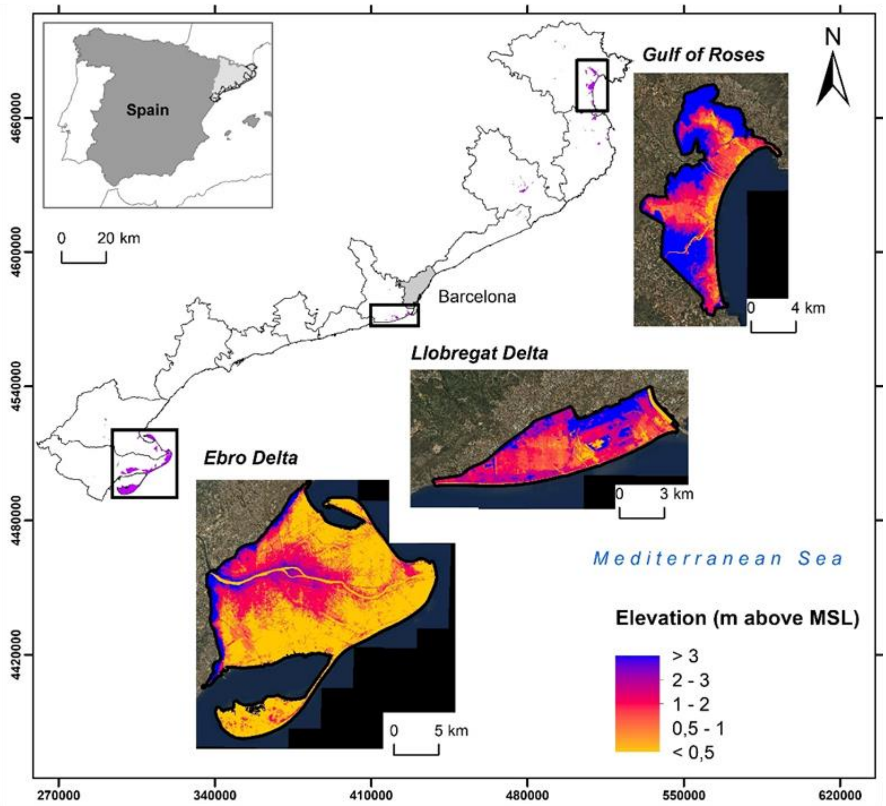


Figure 4.1. The Catalan coast, coastal comarcas and wetlands (shadowed purple areas). The insets are the low-lying study areas with the digital elevation model (see Table 4.1). (The geographic coordinate system is ETRS89/UTM zone 31N).

Low-lying areas along the coast have high environmental value due to habitats that provide high ecosystem service values (e.g., Brenner et al., 2010) including a very large percentage of environmentally protected areas (Brenner et al, 2006); 47% of all the designated wetlands in Catalonia are located in the three selected study areas of the Gulf of Roses, the Llobregat Delta, and the Ebro Delta (hereinafter GR, LD, and ED, respectively) (Fig. 4.1) (Sauri et al., 2010). An overview of the main geomorphologic and socioeconomic characteristics of these areas is given in Table 4.1. These areas include salt, brackish, and freshwater marshes; coastal lagoons; beaches; and sandy dune habitat, which are protected under different legislative provisions including RAMSAR sites, the Natura 2000 Network, and Natural Parks. The ED is one of the largest deltas in the Mediterranean, of which approximately 7,800 ha are protected as a Natural Park. In GR, the Aiguamolls de l'Empordà National Park encompasses 4,730 ha in two discontinuous regions separated by the Empuriabrava marina, where human activities are strictly regulated. In contrast, Baix Llobregat Agricultural Park is dominated by peri-urban agriculture (Paül and McKenzie, 2010), containing 2,900 ha of fruit and vegetable crops with the objective of promoting the integration of agricultural activities with the natural environment.

In the ED, approximately 210 km^2 of the coastal plain are devoted to rice production, generating approximately 98% and 13% of the total yield in Catalonia and Spain, respectively (Zografos, 2017). The land is cultivated under continuous paddy inundation, which requires a constant water supply from the Ebro River distributed via an extensive network of irrigation channels. In the LD area, the main crops are vegetables and fruits, most of which are consumed in the metropolitan area of Barcelona. Agricultural production in the GR is mainly cereals, fruit trees, vines, and olives.

The main factor controlling the inundation of these low-lying areas is their topography (Table 4.1). Thus, ED is most vulnerable to SLR as approximately 53% of its land area is less than 0.5 m above the mean sea level (MSL) (Sánchez-Arcilla et al., 1998). Anthropogenic influences also modulate the natural inundation of these areas. For example, the dense network of irrigation and drainage channels that crisscross the ED plain acts to extend the area of inundation across the deltaic plain (Alvarado-Aguilar et al., 2012).

The configuration of the coastline is also important since, given an absence of flood protection infrastructure, natural landforms serve as a natural barrier to inundation. The LD and GR have a coastal fringe formed by sandy beaches, with coastal dunes of moderate height (García-Lozano and Pintó, 2018) and some inlets and creeks. These areas are fronted by active shorelines able to respond to SLR and maintain some level of protection assuming they have enough accommodation space. On the other hand, the ED has an active sandy outer coastline with small areas of dunes and a passive muddy coastline along two semi-enclosed bays.

Table 4.1. Main characteristics of the study sites (see Fig. 4.1).

		Gulf of Roses (GR)	**Llobregat Delta (LD)**	**Ebro Delta (ED)**
Population (inhabitants in coastal comarcas)		137,951	818,883	145,496
Coastal geomorphology		Active sandy coastline	Active sandy coastline with high dune fields areas	Active sandy outer shoreline and passive muddy semi-enclosed bays
Analyzed surface (ha)		8,504	4,228	33,168
% Surface by elevation range above MSL	<0.5	6.48	6.21	53.06
	0.5-1	9.90	9.11	20.01
	1-2	27.23	37.42	17.35
	2-3	18.72	30.83	6.25
	>3	37.66	16.43	3.32
% Urban surface		12.06	36.66	7.03
% Cropland surface		63.90	26.34	68.42

4.2.2. Data

4.2.2.1. Low-lying areas

The topography of the study sites was characterized using a digital elevation model (DEM) with a grid resolution of 2 x 2 m obtained from Light Detection and Ranging (LiDAR) data from the Cartographic and Geologic Institute of Catalonia (ICGC). Land use and habitats were characterized using two databases: (i) a land-cover map of Catalonia developed by the Ecological and Forestry Applications Research Centre (4th version) and (ii) the habitat distribution maps produced by the Department of Environment of the Catalan Government (2nd version). The former is a high-resolution thematic map obtained by photo-interpretation analysis with a scale of 1:2,500 and a pixel resolution of 0.25 m (Ibàñez i Martí and Burriel, 2010). The latter details habitats in general including those of interest at a European Union (EU) level compiled from aerial orthophotos

(1:5,000) between 2008 and 2012 based on the interpretation and adaptation of the EU CORINE classification (Generalitat de Catalunya, 2018). The official Catalonia Wetland Inventory (Generalitat de Catalunya, 2020) was also used.

4.2.2.2. Sea-level rise

Sea-level rise projections were based on the Intergovernmental Panel on Climate Change (IPCC) AR5 RCP4.5 and RCP8.5 scenarios (50% probability level) (Church et al., 2013), with used values representative of regional estimates as showed in Sayol and Marcos (2018). In addition to this, we have also included a high-impact (H+) scenario to take into account the uncertainties associated with polar ice-sheet processes, which is given by the projection of sea level at 95% probability of the RCP8.5 steric component (Jevrejeva et al. 2014). The inclusion of this scenario has been done from a risk management perspective to include very adverse conditions with a potentially high impact despite their low probability (Hinkel et al., 2015). Relative to 2010, these three scenarios yielded 2100 SLR values of 0.49 m, 0.70 m, and 1.70 m, respectively (Fig. 4.2).

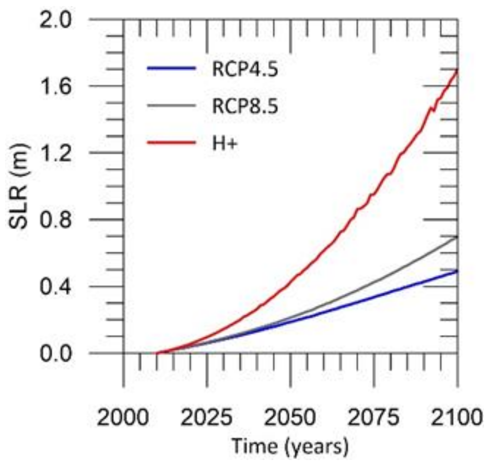


Figure 4.2. Sea-level rise (SLR) scenarios used in this work.

The three study sites are among the areas susceptible to subsidence along the Catalan coast (CADS, 2008). The ED is most affected by subsidence, with reported rates ranging from 1.75 mm/yr (Somoza et al., 1997) to 3 mm/yr (Ibáñez et al., 1997; Jiménez and Valdemoro, 1997). The subsidence in ED under current conditions has been analyzed by

Pérez-Aragüés and Pipia (2015) using DInSAr (Differential Interferometry Synthetic Aperture Radar). They found varying rates across the deltaic plain averaging about 3mm/yr along the deltaic front, which we have selected as a representative rate. Subsidence rates for the LD and GR are poorly studied but lower than the ED, with reported average values of 1.25 mm/yr (Duro et al., 2004) and 0.8 mm/yr (Giménez et al., 1996), respectively.

4.3. Methodology

Our methodology consisted of two steps: (i) the delineation of inundation-prone areas due to RSLR and (ii) the assessment of the impact of inundation on the affected habitats. In both cases, we adopt a pseudo-dynamic methodology that, in the first instance, accounts for the capacity of active shorelines to respond dynamically to RSLR and in the second instance, considered the capacity for habitat conversion.

4.3.1. Delineation of inundation-prone areas

The extent of the area susceptible to inundation under the SLR scenarios was delineated using a pseudo-dynamic bathtub approach. For this, areas below a given water level (i.e., the RSLR of interest) and hydraulically connected to the sea were assumed to be potentially inundated (Gallien et al., 2011; Poulter and Halpin, 2008). Hydraulic connection was defined using the "eight-side rule", where the diagonal and cardinal neighbors are used to determine if a model cell is flooded and to remove isolated low-lying inland areas (Poulter and Halpin, 2008). However, this approach is valid only when the coastal zone is passive, that is, it does not actively respond to RSLR. This includes areas of resistant geology and inner coastlines that do not experience direct wave action. In contrast, exposed low-lying areas fringed by sandy coastlines will react dynamically to changing sea-level conditions (e.g., Fitzgerald, 2008). Here, we assumed an equilibrium-based response of sandy coastlines to RSLR, as depicted by the Bruun model (Bruun, 1962), i.e., an upward and landward translation of the active profile in-pace with rising sea level and maintaining the shape of the equilibrium profile. The validity (and uncertainty) associated to the use of Bruun or, in fact, of any model predicting SLR induced morphological changes has been covered in the literature by different authors (Cooper and Pilkey, 2004; Le Cozannet et al., 2016), and it is still an open question

(Ranasinghe, 2020; Toimil et al., 2020). In the absence of a universally accepted model, here we have used the Bruun model to assess the magnitude of the RSLR-induced shoreline retreat in the study sites. Thus, we followed the approach of Jiménez et al. (2017) when analyzing SLR-induced erosion in Catalonia, whereby the predicted landward response is modulated or prevented by the existence or lack of accommodation space in the hinterland, respectively. Under this assumption, a sandy beach-dune system protecting a low-lying area under current conditions can migrate landwards, while maintaining its relative elevation (and thus protective function) under RSLR provided accommodation space (and sand) is available (Fig. 4.3). Following Jiménez et al. (2017), to reduce the uncertainty in the selection of the closure depth (see Ranasinghe et al., 2012), the Bruun rule was applied using the characteristic values of the inner shelf slope for each study site, calculated from the shoreline to 10 m of depth and thus extending deeper than the medium-term closure of depth along the Catalan coast, which is about 7 m (CIIRC, 2010) (Table 4.2). This permits to account for the expected increase of the limit of the active profile under increasing time scales as those corresponding to RSLR (Cowell et al. 1999).

The landward extension of the active fringe adapting to RSLR was given as the reach of overwash-induced transport, which depends on the wave and water-level climates, and permits the beach to rebuild landwards while the shoreline erodes. This dynamic adaptation approach has previously been used to simulate the long-term (rollover) behavior of the Trabucador barrier system (Jiménez and Sánchez-Arcilla, 2004) and to explain the survival of the Tortosa barrier despite experiencing extreme erosion rates (approximately 40 m/year) in the ED (Valdemoro et al., 2007). The role of overwash transport in transferring material towards the hinterland is modulated by coastal morphology, particularly dune/beach elevation and beach slope (e.g., Durán et al., 2006).

To estimate the critical width, the extension of overwash deposits was identified and measured using aerial photos to obtain an averaged representative value for each study site (Table 4.2). Thus, in each case, beach profiles were assumed to adjust to RSLR as predicted by the Bruun rule provided the hinterland is wider than the projected shoreline erosion plus the critical width. If the existing accommodation space is bounded by an inner fixed boundary, this was assumed the innermost limit for beach migration. In the latter case, the elevation of the physical boundary controls inundation following the bathtub approach.

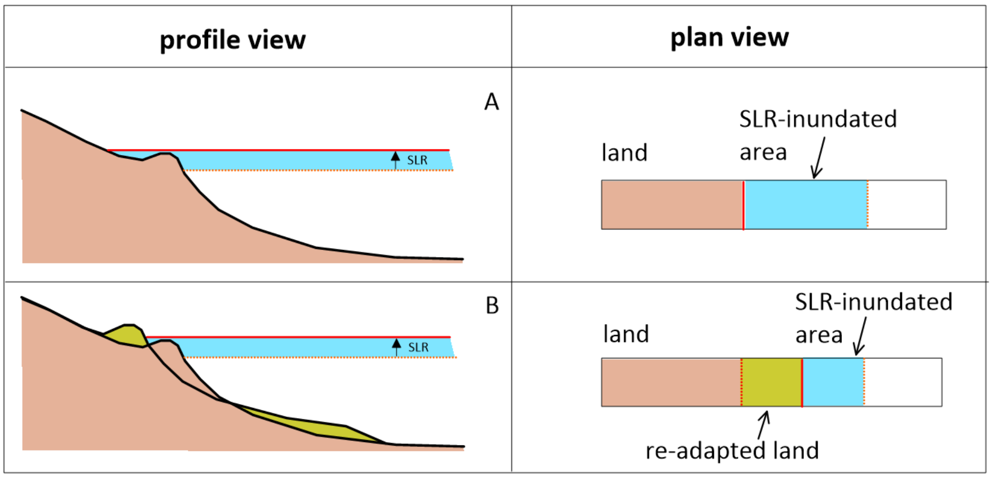


Figure 4.3. Model of SLR-induced inundation. (a) Static-approach and passive inundation following the bathtub method. (b) Pseudo-dynamic equilibrium profile response following the Bruun Rule and inundation following a modified bathtub method. Note: the beach profiles are not to scale.

Table 4.2. Representative values to calculate coastal fringe re-adaptation to RSLR following Bruun rule for each study site.

	Gulf of Roses	Llobregat Delta	Ebro Delta
Shoreface slope	1/87.5	1/100	1/225
Critical beach width (m)	80	60	100

4.3.2. Potential flood damage

Once the areas susceptible to inundation under a given RSLR scenario were delineated, the resulting damage was estimated. One common approach is to determine the area of existing land use and habitats and assume they will be lost if inundated (e.g. Alvarado-Aguilar et al., 2012), which we refer to as the "total damage approach". However, when an inundated area is composed of natural habitats, some habitats have the capacity to change/adapt to new sea-level conditions, which we call the "conversion approach". The conversion approach is similar to that employed in coastal landscape models in which a given habitat affected by inundation has an assumed capacity to change/adapt depending on its properties and the new conditions it is exposed (Kirwan et al., 2010; Lentz et al., 2016). The evolution of habitats within an inundated area is evaluated by applying a series of conversion rules linking their current spatial distribution and their expected capacity to respond to each RSLR scenario.

First, coastal habitats were re-classified into generalized types based on their distinctive responses to SLR according to geomorphology, ecology, and level of development. These categories and general summaries of the land-cover types and main habitats found in each study site are provided in Annex B, Table B1. The differences in habitats within a given category correspond to site specificities that depend on local characteristics such as geomorphology, freshwater availability, and land use.

The first variable affecting a habitat's susceptibility to inundation is vertical distribution and distance with respect to mean sea level. Here, we assumed that specific habitats thrive within a certain elevation range according to their salinity tolerance and resilience to flooding and physical (wave) disturbance. To this end, habitat and topographic data were jointly analyzed to evaluate the vertical distribution, with resulting distribution ranges varying among the study sites (Fig. 4.4) due to their local characteristics, particularly topography and water flux across the coastal plain (see also Benito et al., 2004). Considering the vertical distributions of existing habitats (Fig. 4.4 and Table B1, Annex B), a series of basic transition rules were applied (Table 4.3). This followed a simplified version of previously adopted dynamic transitions including the SLAMM (Clough et al., 2016; Craft et al., 2009; Glick et al., 2013; Traill et al., 2011) and is similar to other simplified approaches (Lentz et al., 2016).

An important aspect to consider in habitat response is the effect of hydraulic connectivity between the affected area and the sea. This was represented by delineating areas of total and partial inundation, which are inextricably linked to vegetation distribution (Mogensen and Rogers, 2018). To this end, we included tidal influences using the following three vertical levels: (i) the mean sea level (MSL), given by the target RSLR; (ii) the high-sea level (HSL); and (iii) the low-sea level (LSL). The HSL and LSL bound the intertidal zone around the future MSL, which corresponds to an average astronomical tidal amplitude of 0.20 m. Thus, when analyzing the inundation extent of each RSLR scenario, the pseudo-dynamic bathtub approach was applied as delimited by the MSL. Two additional inundation simulations were then performed, the first to derive the area below the HSL and the second to derive the area below the LSL. The area below the LSL was taken as the area of permanent inundation, and the intertidal zone between the HSL and LSL was taken as the area of temporary inundation. Importantly, to delineate the area below the HSL, hydraulic connectivity criteria were applied. This meant that areas within this elevation range but which are isolated by the presence of a physical barrier/infrastructure were not inundated. Habitat conversion under a given RSLR scenario was controlled by its location with respect to the MSL (Table 4.3). The transition rules did not consider the time required for habitats to accommodate new conditions, but as a general rule, the longer they have to reach new conditions, the greater the capacity to change (Spencer et al., 2016). This time factor is further discussed in Section 4.5.2.

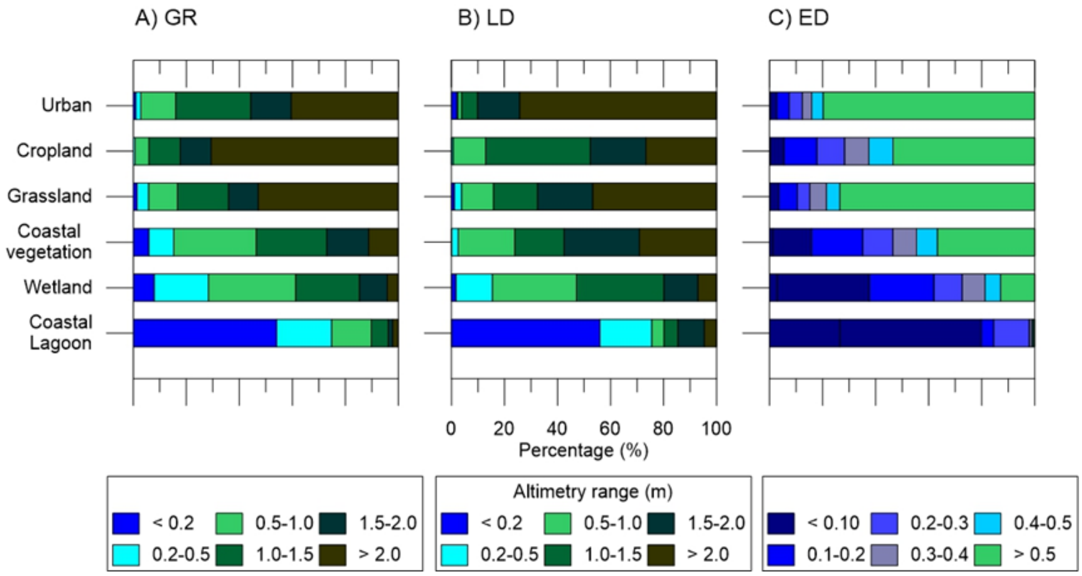


Figure 4.4. Vertical distribution of main habitat types in each study area. Values are the percentage (%) of a given habitat in a given altimetry range as a proportion of the total habitat surface within the study area. Note that the altimetry interval classes are different for each study area.

Table 4.3. Transition rules determining habitat shifts and associated sea-level criteria.

Initial habitat type	Final habitat type	Sea-level criteria
Cropland Grassland Temperate forest	Halophyte vegetation	HSL–MSL
	Transitional wetland	MSL–LSL
	Coastal lagoon	<LSL
Coastal vegetation Wetland	Transitional wetland	MSL–LSL
	Coastal lagoon	<LSL
Coastal lagoon	Coastal lagoon	<MSL

The conversion rules shown in Table 4.3 were applied assuming two boundary conditions: (i) no modification to existing structures in the floodplain (e.g., dikes, levees, channels, etc.) and (ii) negligible sediment input to the floodplain. The first condition could be changed to simulate the effect of floodgates or barriers as adaptation measures to RSLR. However, as our primary objective was to assess impact, we chose to evaluate the effect of inundation without anthropogenic influence other than the existing infrastructure. The second condition limits the inherent capacity of wetlands to adapt in response to SLR (Mogensen and Rogers, 2018; Spencer et al., 2016). However, this assumption reflects current conditions in the region and especially in the ED (e.g., Ibáñez et al., 1997; 2010). Thus, instead of considering vertical accretion rates to control habitat shifts (Tabak et al., 2016; Traill et al., 2011), the applied rules were based on relative elevation, i.e., sea-level criteria and current vertical distribution of each habitat type.

Finally, the effect of saltwater intrusion on cropland areas was also considered, as this is a major threat to agricultural lands in the region (Butcher et al., 2016; Tully et al., 2012). Under this scenario, impacts are expected to differ between the study areas given that their main crop types are not the same (see Genua-Olmedo et al. (2016) for the ED, Soy-Massoni et al. (2016) for the GR, and Serra et al. (2018) for the LD), meaning variable salinity thresholds with respect to impacts on yield (e.g., Maas and Grattan, 1999; Machado et al., 2017). Furthermore, local geomorphology dictates the suitability of an area for agriculture and crop type (Fig. 4.4). For example, given the low or very low tolerance of existing crops to saltwater intrusion, croplands are sparse in low-lying areas close to the water level in GR and LD (<1% of the total surface). Therefore, a minimum elevation threshold of 0.5 m with respect to the simulated future water levels was applied for the assumed maintenance of croplands; agricultural land below this level under a given SLR scenario was assumed to be abandoned due to salt intolerance and the likely rapid colonization by other salt-tolerant vegetation (see Meyer et al., 2016). Such conversion of abandoned agricultural land to halophytic vegetation communities (or barren land) follows ecosystems connectivity, helping to preserve linkage between them (Fagherazzi et al., 2019; Kirwan and Gedan, 2019). The application of this agricultural transition rule was specific to GR and LD, as agriculture in the ED is devoted to rice production in paddies at all elevations along the delta plain (Fig. 4.4), which are maintained by active freshwater inundation, which productivity also depends on elevation (e.g., Genua-Olmedo et al., 2016).

4.4. Results

4.4.1. Flood analysis and potentially inundated areas

For comparison, Fig. 4.5 shows the ED inundation extent for the entire range of RSLR scenarios based on both the classical (i.e., passive inundation) and pseudo-dynamic bathtub approaches. By 2050, including natural coastline adaptation to SLR decreased the inundated area by approximately 34.7% under RCP4.5 and RCP8.5, and by 21.1% under the H+ scenario. By 2100, the protection provided by the morphodynamic coastal response decreases, with the inundated area being just 11.3%, 5.1%, and 2% lower than that calculated by using the passive bathtub approach for RCP4.5, RCP8.5, and H+ scenarios, respectively.

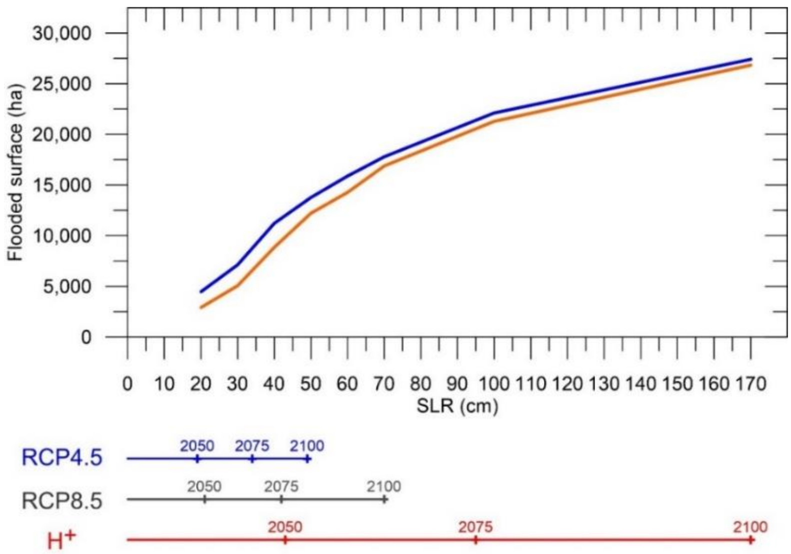


Figure 4.5. Computed inundated surface (ha) using the classical bathtub approach (blue line) and pseudo-dynamic method (orange line) in the Ebro Delta (ED) under the range of considered RSLR scenarios. Corresponding timelines for SLR under the selected scenarios are shown at the bottom.

Therefore, the inclusion of the capacity for active sandy shorelines to respond dynamically to SLR yielded a smaller inundation extent relative to a passive inundation approach, and this effect was most pronounced under the low-medium RSLR scenarios. However, as RSLR increases, the natural protective effect decreased, reflecting site-specific modulation via anthropogenic modification of the deltaic plain (Fig. 4.6). Under lower RSLR conditions, most of the coast is protected by beaches, with inundated areas occurring (i) along the inner bays where there is no beach protection; (ii) in the inner part of the spits; and (iii) in areas with very flat beaches (<RSLR) (indicated by the light-blue areas in Fig. 4.6). However, if a beach can maintain its relative elevation with respect to MSL—as the pseudo-dynamic approach assumed—the hinterland should be protected. This effect can only be detectable provided there are very low sandy stretches (i.e., below the target level); if the entire coast is higher than the simulated RSLR, the computed inundation extent of both methods will be the same.

The capacity for such a dynamic protective response is lost in some locations due to the lack of accommodation space, which is constrained by the existence of infrastructure in the hinterland. In the ED, this was mainly identified in the northern region, where some narrow beaches are backed by levees causing coastal squeeze (see the red square in Fig. 4.6c), with the elevation of this infrastructure (with no adaptation capability to SLR) being the main control on inundation. Accordingly, approximately 1,435 ha was flooded assuming 40 cm of SLR primarily as a result of the beach breaching in the absence of active adjustment. The distribution of floodwater across the deltaic plain is another element controlling the magnitude of inundation. This will largely be controlled by the topography of an area, but in the case of the ED, the existing network of channels crisscrossing the area extend the inundation from adjoining areas (Fig. 4.6d).

The computed inundation-prone areas for the three study sites under the considered scenarios are shown in Table 4.4 and Fig. 4.7. The results reflect the influence of geomorphology and relief, with the ED being the most vulnerable site, and GR and LD only significantly affected under high RSLR conditions due to relatively high beach profiles protecting the hinterland and their higher elevation. This higher topography also implies that differences in the inundation extents determined using the static and modified bathtub approaches will be relatively low in the GR and LD because, as previously noted, this is only detectable when beach/dune heights are lower than the RSLR scenario.

The difference in vulnerability is reflected in the percentage of the affected surface. Thus, by 2050, the inundated surface in the GR and LD represents less than 1% and 2% of the total area under both RCP and H+ scenarios, respectively. In comparison, the proportion of the ED inundated under these scenarios increase by 9% and 27%, respectively (Table 4.4). Except for the ED, by 2100, the increase in the magnitude of

RSLR under RCP4.5 and RCP8.5 did not result in a significant increase in the inundated area. Specifically, the long-term projection of the inundation extent in the GR and LD increased by less than 7% under RCP8.5. In comparison, in the ED, the affected area covered approximately 50% of the deltaic plain under RCP8.5. As expected, the vulnerability of these systems to the H+ scenario significantly increased, with approximately 35% of the GR and LD, and 80% of the ED, being susceptible to inundation.

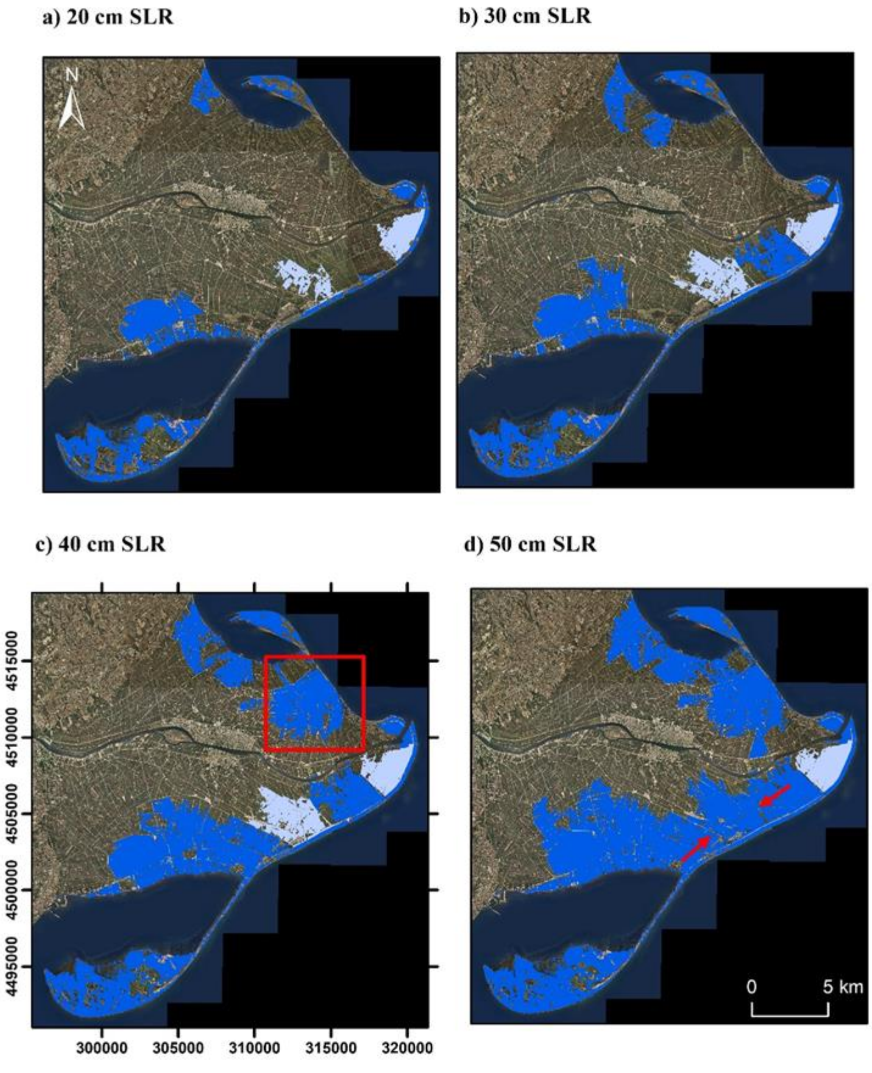


Figure 4.6. Inundation-prone areas in the ED under different RSLR scenarios. Light-blue shading indicates additional areas of inundation not accounting for dynamic beach response (i.e., computed using the static bathtub approach but not the pseudo-dynamic method). Active beach adaptation to RSLR is prevented when accommodation space is insufficient (e.g., the red square in (c) where narrow beaches are backed by infrastructure). Due to the network of channels crisscrossing the plain, some areas otherwise protected by a beach can be inundated by water from adjoining areas (red arrows in (d)). (The geographic coordinate system is ETRS89/UTM zone 31N).

Table 4.4. Inundation-prone surface (ha) and percentage of the study site area (%) by using the pseudo-dynamic inundation method under different RSLR scenarios at given time horizons.

Year	Scenario	GR		LD		ED	
		Ha	%	ha	%	ha	%
2050	RCP4.5 RCP8.5	83	0.98	40	0.94	2,923	8.81
	H+	169	1.99	67	1.59	8,856	26.70
2100	RCP4.5	224	2.64	99	2.34	12,215	36.83
	RCP8.5	579	6.81	169	4.01	16,881	50.90
	H+	2,970	34.92	1,518	35.91	26,838	80.91

4.4.2. Flood damage analysis

Fig. 4.8 shows the relative percentage of habitats (by area) affected by inundation at the three study sites under the different RSLR scenarios. Although the evolution of affected surfaces with RSLR is similar, significant differences exist in the extent of inundation and the shape of the curve for each habitat type, largely reflecting their vertical distributions (Fig. 4.4). The affected surface area for each habitat by 2050 and 2100 under the tested scenarios are given in Annex B, Tables B2, B3, and B4 for GR, LD, and ED, respectively.

The most affected habitats are those found at the lowest elevations, namely coastal lagoons and wetlands. Although this was common between the three sites, the greatest susceptibility was simulated in the ED, where more than 90% of the wetland area is inundated assuming a RSLR of 70 cm (broadly equating to 2100 under the RCP8.5 scenario). Under the same conditions, 38% and 16% of the existing wetlands in the GR and LD are inundated, respectively. This general trend also applies to lagoons, although differences between the GR and LD are higher (Fig. 4.8). This difference is even more pronounced for agricultural lands, where a 70 cm RSLR resulted in the submergence of approximately 50% in the ED compared to < 1% in the GR and LD. Under the higher RSLR scenarios, agricultural lands in the GR and LD were increasingly affected but to a much lesser extent than in the ED.

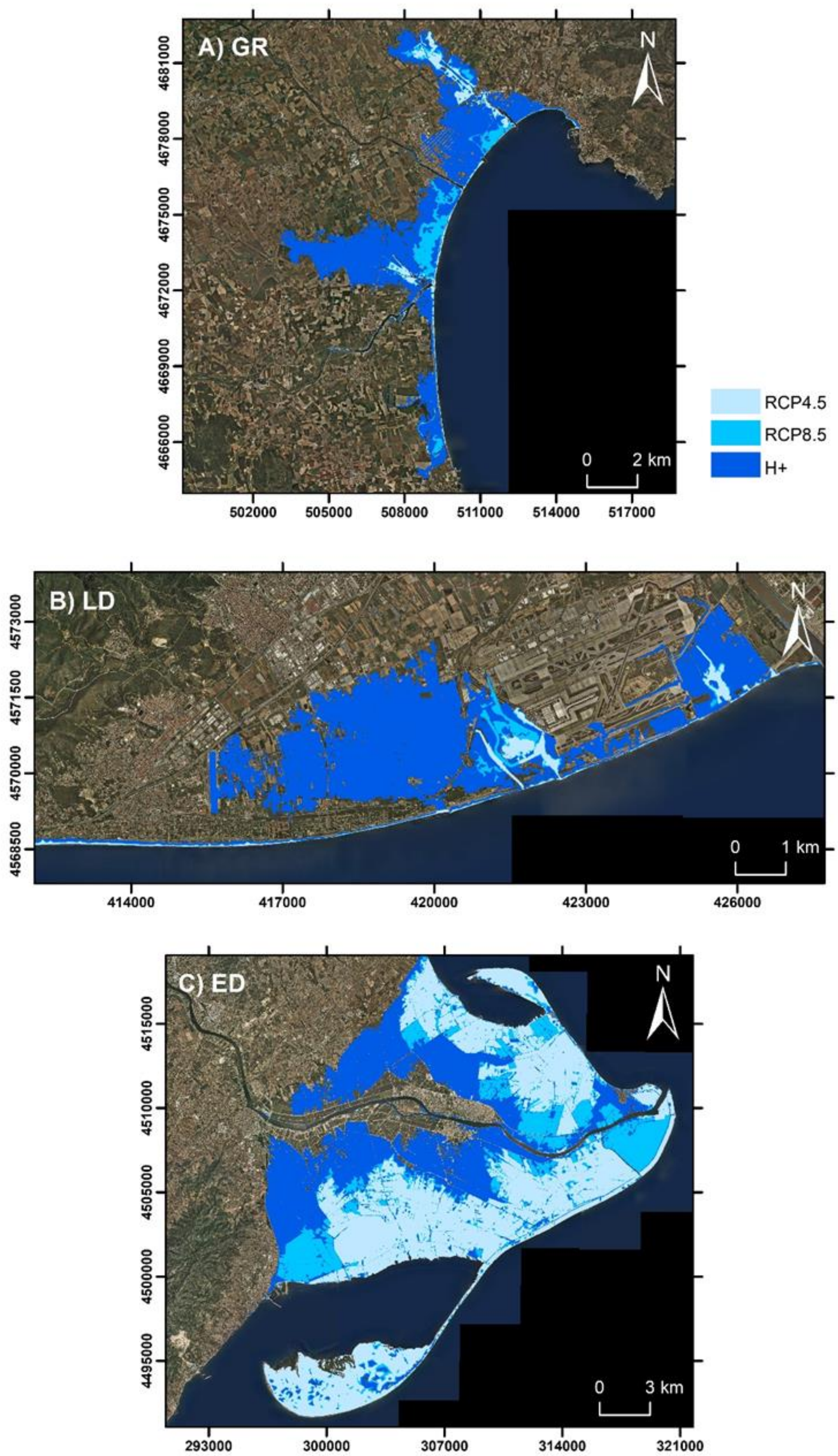


Figure 4.7. Inundation extent for 2100 under different SLR-scenarios at the (a) GR, (b) LD, (c) ED. (The geographic coordinate system is ETRS89/UTM zone 31N).

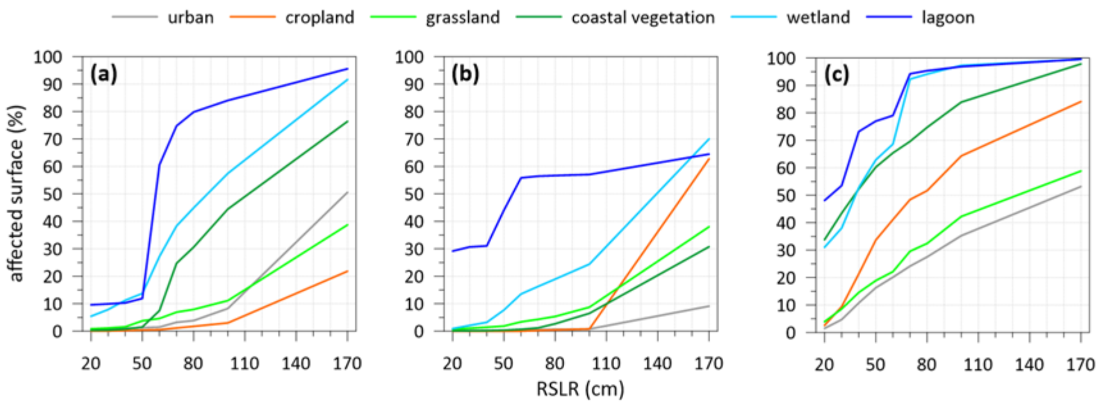


Figure 4.8. Simulated proportion (in %) of main habitat types inundated in the plain of (a) GR, (b) LD, and (c) ED.

According to our methodology, habitats occupying inundated areas are not necessarily lost as they have some capacity to adapt to the new conditions. Tables B2–B4 in Annex B show the evolution of habitat surfaces at each site under the different scenarios by 2050 and 2100. Natural habitats, which are located at the lowest elevations and are most directly affected by inundation, are also more likely to evolve or migrate in response to changing sea levels, and they are coastal lagoons, coastal vegetation, and wetlands. Fig. 4.9 shows the projected habitat evolution in the three study sites by 2100 under the RCP8.5 scenario.

With the adopted rules, the largest habitat variation was estimated for coastal lagoons whose surfaces increase with time and with the magnitude of SLR, and they occupy almost all of the projected inundated surface. By far, the largest increase occurs in the ED, where a significant portion of the deltaic plain was inundated, generating a large, shallow waterbody partially protected by the sandy coastal fringe, with different eco-geomorphological characteristics depending on the site. Along the inner northern and southern bays, saltwater open lagoons occur due to their passive shorelines. On the other hand, along the seaward coast, brackish-saltwater leaky lagoons occur, partially protected by a narrow sandy barrier (Fig. 4.9c). In the LD, the new lagoon surfaces would have a similar typology to the existing ones, mostly chocked lagoons elongated perpendicular to the coast (Fig. 4.9b). This is due to the relatively high coastal profile that results in inundation progressing through existing channels that connect lagoons to the open sea. Lastly, the simulated future lagoon surface in the GR has a combination of elongated chocked brackish lagoons at the northern end of the bay and restricted/leaky lagoons in the central part (Fig. 4.9a).

For wetlands, the largest conversion was also projected in the ED. At relatively low RSLR values (RCP8.5 by 2050), an increase of approximately 25% was predicted with losses due to full submergence (i.e., conversion to lagoons) compensated by the conversion of rice fields and areas of coastal vegetation in the intertidal zone to transitional wetlands. Importantly, approximately half of this projected area would not be captured without considering the dynamic adaptation of habitats (i.e., the "total damage approach" in Table B4, Annex B). Under higher RSLR values (RCP8.5 by 2100), the wetland surface decreases to approximately 79% of the original values. In the LD and GR, the simulated variations are different from the ED as topography significantly differs (Fig. 4.9). Thus, at low RSLR values (RCP8.5 by 2050), change in the wetland surface is negligible. With a higher rate of change (RCP8.5 by 2100), the wetland surface area in the GR and LD decreased to 71% and 90%, respectively (Tables B2 and B3, Annex B).

Coastal vegetation shows a similar variation to wetlands, where a new fringe of halophyte vegetation developed close to the sea level affected by high tides (the HSL–MSL range). The largest variation was found in the ED, where a significant increase of up to 240% was simulated relative to the current state under low SLR scenarios (RCP4.5 and RCP8.5 by 2050). However, under the higher SLR scenario (e.g., RCP8.5 by 2100), although the area occupied by coastal vegetation is larger than under current conditions, it progressively decreased due to the effects of existing infrastructure. This change in areas of coastal vegetation was also observed in the GR and LD but was modulated according to their topographic and spatial characteristics. These factors determine the extension of halophytic vegetation in comparison with losses via direct inundation and landward beach migration, whereby current coastal vegetation could be buried by overwash deposits (Tables B2 and B3, Annex B). The simulations also indicate that the composition of new areas of wetland and coastal vegetation would differ from the current communities via large-scale conversion to transitional wetlands, and halophytic communities would occur at the expense of freshwater vegetation and agricultural land.

Beach and dune habitats were simulated to decrease at all sites, with spatial patterns driven by the effect of existing infrastructure that limits landward migration. Thus, considering the expected change by 2050 under the RCP8.5 scenario, beaches decrease to approximately 96%, 89%, and 86% of their current area for GR, LD, and ED, respectively. As expected, the loss of beaches significantly increases beyond 2050 due to

SLR acceleration and the lack of accommodation space for natural adaptation (Tables B2, B3 and B4 in Annex B).

Finally, agricultural lands were simulated as being the most negatively affected habitat, with estimated losses larger than those resulting from direct inundation given no capacity to adapt and because the fringes closest to the projected water levels are developed preventing their future use for agriculture. Thus, croplands currently occupying the future intertidal zone under a given RSLR scenario are likely to be replaced by halophytic vegetation and transitional wetlands. Moreover, in the GR and LD, agricultural land located at an elevation below +0.5 m with respect to future MSL is too saline to support the current cropping systems. For example, under a relatively low RSLR scenario (2050 under RCP8.5), losses of cropland due to habitat conversion are 1.5%, 2.6%, and 5.1% above those from direct inundation in the GR, LD, and ED, respectively. Under the same scenario, by 2100 the relative increases in cropland losses are 8.9%, 26.1%, and 3.3% for GR, LD, and ED, respectively. This reflects the potential abandonment of the orchards and crops on the higher land in the GR and LD due to the saltwater intrusion.

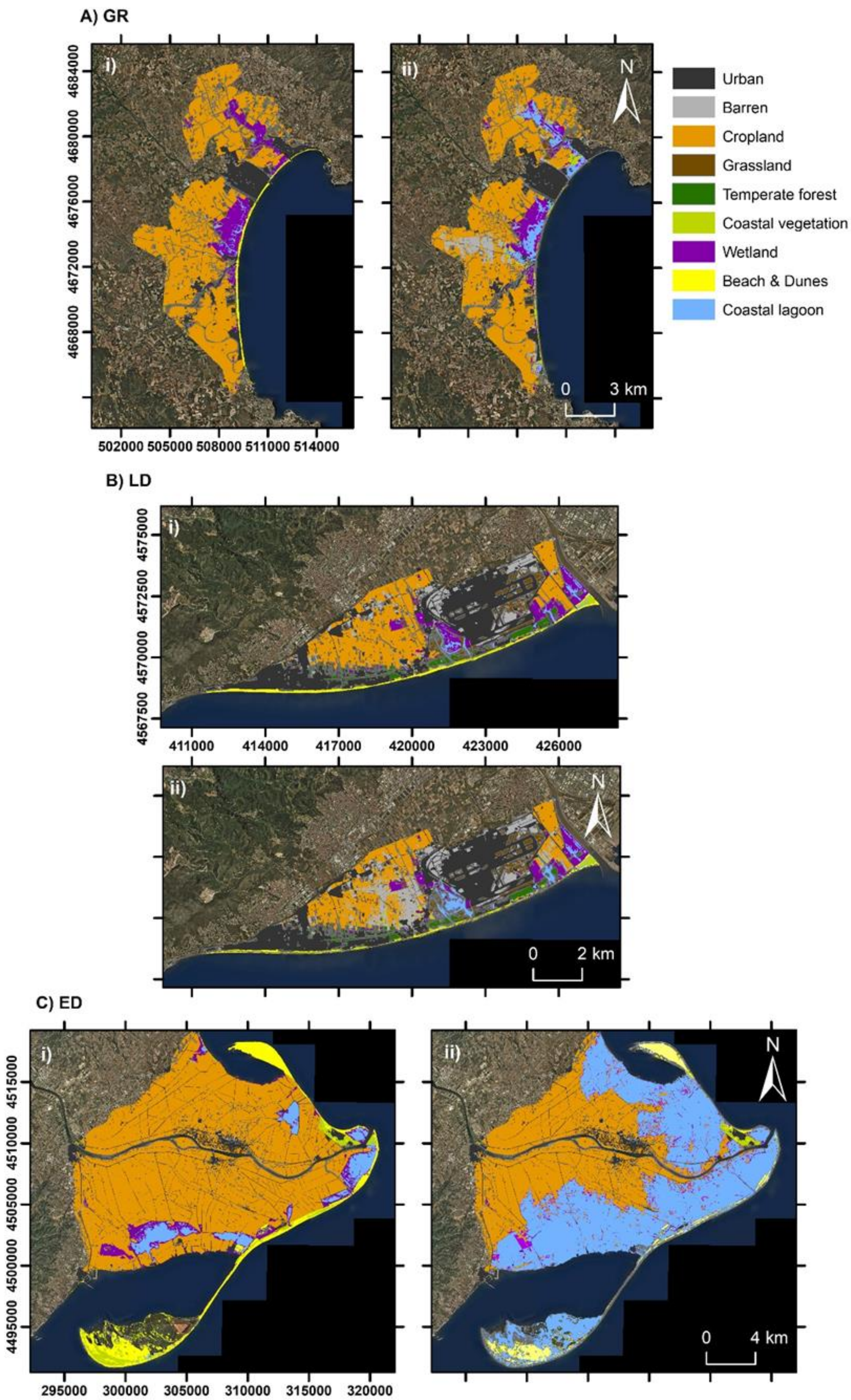


Figure 4.9. Habitat distribution under (i) current conditions and (ii) projected changes assuming habitat conversion by 2100 under RCP8.5 scenario at (a) GR, (b) LD; and (c) ED. (The geographic coordinate system is ETRS89/UTM zone 31N).

4.5. Discussion and conclusions

4.5.1. Methodological aspects

We developed a pseudo-dynamic method to account for active shoreline responses to RSLR in predictions of the inundation of low-lying areas of sandy coasts. This approach is based on the coupling of an equilibrium-based coastal response and classical bathtub modeling approaches. Although simple, it permits the movement beyond a passive inundation model, which ignores the dynamic response of coastal environments to RSLR (e.g., Passeri et al., 2015).

The dynamic adaptation of sandy shorelines to RSLR has been simulated by using the Bruun model, which was implemented considering the availability of accommodation space in the hinterland. When no obstacles exist, beaches adjust by migrating upward and landward so that their relative elevation is maintained and, consequently, afford the same level of protection against inundation. However, where a physical barrier prevents this landward migration, beaches will progressively erode and lose their dynamic protective capacity, and inundation will ultimately be controlled by the height of the barrier. Thus, a lack of accommodation space depends not only on the existence of a barrier but also on the rate of SLR, which determines the velocity of beach landward migration to reach the barrier. Our approach can be adapted for other models of coastal response to SLR (e.g., Dean and Maurmeyer, 1983; Ranasinghe et al., 2012; Rosati et al., 2013), with the protection afforded by a beach ultimately controlled by the dynamic response to future conditions.

It has to be noted that we have not included shoreline changes other than RSLR-induced, and this should be equivalent to “isolate” the RSLR component in the long-term behavior of these areas. However, other factors such as river sediment supplies and longshore and cross-shore sediment transport patterns would also contribute to their long-term evolution (e.g., Jiménez et al., 1997; Jiménez and Sánchez-Arcilla, 2004). Integrating all these components into a single long-term morphodynamic model is an issue that is far from being solved at present (e.g., Ranasinghe et al., 2012). Importantly, our approach is closer to reality for assessing the inundation extent in sandy coasts, being relevant for low-lying beaches lower than the target RSLR. Thus, when we compared the computed inundated extents for the three study areas with those obtained by using the conventional bathtub approach, significant differences were only found for the ED (a <35% in the inundated area by 2050 under the RCP8.5 scenario). Although this trend should be maintained for higher RSLR provided accommodation space is available, both methods tended to produce similar results, with a reduction in the inundation extent of just about 5% by 2100. However, this is largely attributed to the hydraulic connectivity of the ED plain, where seawater entering through passive areas is distributed across the plain via the channel network (see also Alvarado-Aguilar et al., 2012).

We also implemented a simple method to account for the possibility of habitat conversion following inundation. Thus, SLR-induced damage projects are modulated and, as a consequence, may affect decision-making and the development of adaptation strategies. In most projections, an assumption is made that all inundated areas of land are lost. While this can be acceptable for highly modified environments, this may lead to unrealistic damage estimations for those natural systems able to adapt to future conditions.

There are some advanced tools to simulate habitat conversion, such as the SLAMM, which was specifically used to characterize wetland response under future sea-level scenarios (Clough et al., 2016; Craft et al., 2009; Glick et al., 2013; Traill et al., 2011). This model allows for the dynamic assessment of SLR, transitioning away from simple and static inundation models, although concerns regarding application in different geomorphological, ecological, and hydrological settings have been raised (Oreskes et al., 1994; Rykiel, 1996). Nevertheless, the use of complex landscape models provides detailed information on habitat responses despite the constraints of time-consuming computational effort and model calibration (Mcleod et al., 2010). Here, we followed a much simpler approach based on the same underlying concept—that habitats have a capacity to adapt to new conditions—formulated as a series of rules based on ecological succession, tolerance to inundation and/or salinity, vertical distribution, and location with respect to the MSL. This approach considers the intertidal zone associated with the future MSL as a buffer area of potential high environmental value. When located within the flood plain outside the sandy fringe, areas of typical vegetation will naturally evolve, with habitat shifts being controlled by hydraulic connectivity to the sea and salinity tolerance (e.g., Rogel et al., 2000). This is similar to the assumptions of some existing models for wetlands that predict vegetation distribution based on dominant hydrodynamic conditions, such as water depth and duration of inundation (Morris et al., 2002; Todd et al., 2010).

Although the capacity for wetland adaptation is highly linked to sediment availability and vertical accretion (Cahoon et al., 1995; Kirwan et al., 2010; Reed, 1995), this was not considered here as sediment input to the study areas is practically zero. For example, in the case of the ED, significant retention of riverine sediments behind dams in the upper Ebro River catchment (up to 99%) dramatically reduces the capacity for the vertical accretion of the delta plain in response to SLR (Ibáñez et al., 1996; 1997). Indeed, the suspended sediment load is currently <0.01 g/l (Rovira et al., 2012), meaning delta is unable to grow and suffers from intense coastal reshaping by wave action (Jiménez and Sánchez-Arcilla, 1993; Jiménez et al., 1997). This anthropogenic impact on hydrology and sediment budgets can disrupt the eco-geomorphological feedbacks needed to adjust to SLR and hinder the natural capacity of systems to survive (Rodríguez et al., 2017; Sandi et al., 2018). Therefore, the conversion rules we applied in our simulations are appropriate for the target study sites but should be adapted for application elsewhere if conditions permit vertical accretion. Overall, although a broadly simple approach, our methodology improves the impact assessment of the RSLR-induced inundation in low-lying natural areas both with respect to inundation extent and potential habitat loss. Importantly, the approach can be easily implemented in a GIS environment and, thus, used as an additional element in the decision-making process to design adaptation strategies in this type of environment.

4.5.2. Inundation-driven impacts on study sites

While the study sites are considered the most sensitive areas of the Catalan coast to SLR-induced permanent inundation, they show very different sensitivities depending on the configuration of the sea-land border, topography, geomorphology, and degree of human impact on the floodplain. The ED was found to be most vulnerable to SLR inundation due to (i) a very long passive coastline unable to protect the floodplain behind along the semi-enclosed bays, where floodwaters affect a large area of the hinterland; (ii) a very low relief, which exposes a large proportion of the floodplain to inundation under relatively low RSLR scenarios (approximately 73% of the plain is <1 m above MSL); and (iii) a dense network of channels crisscrossing the plain that, although may act as barriers, if not managed appropriately, can facilitate the transfer of floodwaters across the plain. In contrast, the LD and GR show more resilient configurations due to (i) coastlines formed by relatively wide sandy beaches with dunes able to adapt to changing sea levels while maintaining a good level of protection; (ii) limited exposure of the lowest part of the plains due to their topography (approximately 15% of their plains are <1 m above MSL); and (iii) the main areas of water entrance onto the plain are existing outlets connecting lagoons and rivers with the open sea, which restricts inundation in these areas.

In this context, it is important to highlight the need for reliable estimates of local subsidence rates, as these will determine the local acceleration of SLR and, consequently, modulate possible differences in RSLR under the same climatic scenario, as those reported by Vacchi et al. (2016) and Vecchio et al. (2019) for the Mediterranean coast. In the analyzed areas, used subsidence rates are based on existing local estimates, with GR and LD being the sites with a lower coverage and, consequently, with a larger associated uncertainty. Differences in vulnerability among study areas are also reflected in the expected impacts of SLR-inundation on representative habitats. For croplands, the ED is considered the only site to be significantly impacted by inundation based on both the relative and absolute magnitudes of the affected area. This is due to the extension and covered range of elevations of the deltaic plain surface, which indicated a direct impact (by inundation) on cultivated land of between 10% and 52% by 2050 and 2100, respectively, under RCP8.5. Existing studies on the impact of SLR on rice production due to salt intrusion have found a similar pattern (Genua-Olmedo et al., 2016) due to the relationship between soil salinity and surface elevation. Considering these results, it is expected that the productivity of agriculture land above the simulated inundation levels will also decrease due to progressive soil salinization.

The simulated impact of inundation on agriculture is much smaller in the LD and GR compared to the ED, both in absolute and relative terms, with approximately 26% and 10% of agricultural land affected, respectively, by 2100 under RCP8.5. It is important to note that these projections only account for direct inundation and do not reflect areas affected by saltwater intrusion, which would lead to higher losses in the GR and LD. For the LD and GR, as most of the agriculture lands affected by SLR would become disconnected from water, cultivation will likely be abandoned. This implies a net loss of ecosystem services provided by agricultural lands (e.g., Tscharnkte et al., 2005), including cultural services (Serra et al., 2018; Soy-Massoni et al., 2016). In the ED, the inundation of croplands maintained hydraulic connectivity in our simulations, driving the development of a shallow lagoon along the entire coast (Fig. 4.9). Thus, the combination of a wide and gently sloping topography fringed with coastal vegetation, lagoons, and wetlands at the seaward boundaries of rice fields and protection from direct wave action afforded by an active sandy coastline provides ideal conditions for marsh development and migration. Indeed, in addition to vertical accretion, transgression into adjacent uplands is a primary mechanism for marsh survival, where gently sloping uplands favor marsh migration (e.g., Kirwan et al., 2016).

The current configuration of the ED plain appears to be the most important factor determining differences in the degree of inundation as well as the induced damage. On the one hand, the inundation extent is strongly controlled by the dense channel network crisscrossing the delta plain (Alvarado-Aguilar et al., 2012). On the other hand, this network moderates habitat migration and the formation of new natural areas. To enhance this landscape shift from agriculture to natural habitats formed by lagoons and marshes, existing barriers in the plain (e.g., channels and other minor infrastructure) should be removed, as they function as the main obstacle for marsh expansion by upland migration (for example, Borchert et al., 2018; Wolters et al., 2005). This boundary effect has also been considered by Prado et al. (2019) who analyzed the effects of SLR on the pristine and anthropic configurations of the ED.

The largest expansion of natural habitats was predicted for lagoons. In the case of the LD and GR, lagoons increased in area but maintained their typology by expanding from their current configuration over the surrounding wetlands according to local topography. This topographic control means that the LD is expected to be the site experiencing the lowest degree of lagoon expansion—approximately 184% by 2100 under RCP8.5 compared to 600% for the GR. In absolute terms, the simulated lagoon surface in the ED under this scenario will be approximately 0.16 times the current one. In contrast, once the critical rate of SLR at which wetlands drown is exceeded, the extensive inundation of the ED plain would result in a significant increase in lagoon surface area (approximately 565% by 2100 under RCP8.5) and significantly altered typology. A large proportion of this new surface would be occupied by saltwater open shallow lagoons along the bayside shorelines and brackish-saltwater leaky lagoons along the seaward coast. Under current conditions, freshwater inputs to lagoons occur via irrigation channels, a practice that can be maintained under future conditions.

Importantly, the ecological characteristics of converted natural areas may differ from the existing ones. Projected wetland areas would be dominated by saltwater ecosystems, whereas under current conditions, they are a mix of saltwater, brackish, and freshwater environments. In this context, salinity is generally one of the most important factors determining coastal wetland habitat type (e.g., White and Kaplan, 2017), and for the three study areas, SLR-related inundation will drive a shift in plant communities to salt- and flood-tolerant wetlands (Day et al., 2000; McKee and Mendelssohn, 1989), having implications for wetland management (White and Kaplan, 2017).

The time available to adapt becomes crucial when considering the ability of habitats to naturally respond to changing sea levels. We assessed the impact of inundation as a function of projected water levels but did not consider the time taken to reach these levels. Indeed, the rate of rising will strongly affect the capacity of these systems to respond. Thus, the longer the time taken to reach new conditions, the higher the likelihood that a system can respond via ecological succession. This temporal effect was examined for coastal marshes by Kirwan et al. (2010), demonstrating threshold SLR rates that lead to marsh submergence and irreversible conversion to unvegetated areas. Such thresholds are site-specific and depend on factors such as sediment availability and tidal range (e.g., Kirwan and Megonigal, 2013; Kirwan et al., 2016). This potential effect is illustrated for the ED in Fig. 4.10, which shows the inundation extent for three elevation ranges (0–0.1 m, 0.1–0.2 m, 0.2–0.5 m) under the simulated SLR scenarios. Although the extents are the same (being determined by the selected elevation range), the time required to inundate each segment and, consequently, the time for adaptation varies. Under RCP4.5 and RCP8.5, the time to adapt at the lowest intervals (<0.1 m and <0.2 m) would be similar, becoming inundated by 2025–2040 and 2040–2060, respectively. However, at higher elevations (<0.5 m), the time available is approximately 20 years shorter under RCP8.5. In the case of the high-impact H+ scenario, the time for adaptation at all elevation ranges drastically decreases relative to RCP4.5 by 5, 20, and 40 years at <0.1 m, <0.2 m, and <0.5 m, respectively.

The inclusion of time as a variable in assessments of potential inundation damage is important because it has direct consequences in terms of (1) flood management, by constraining the design, development, and implementation of adaptation strategies, and (2) habitat response, by increasing the probability of adaptation and ecological succession.

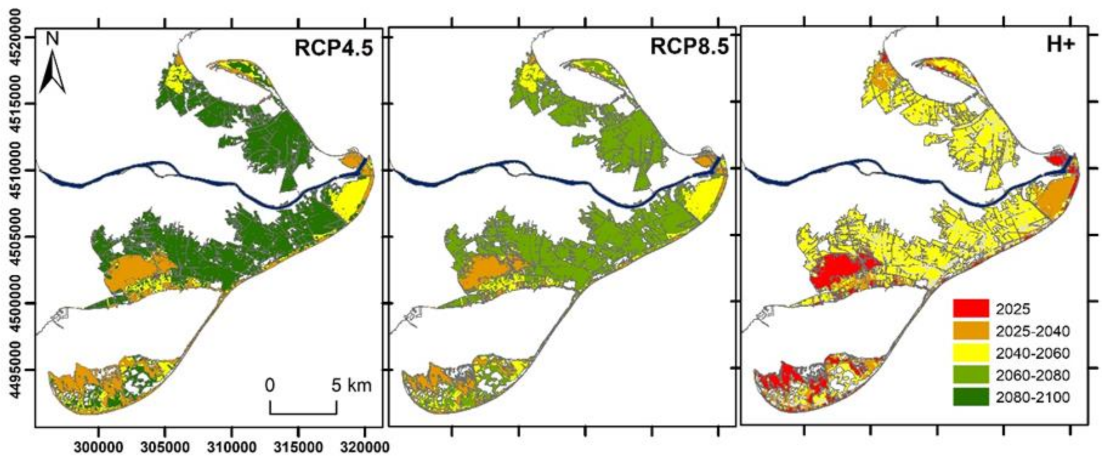


Figure 4.10. Timeframes of inundation from 2025 to 2100 in the ED at different elevation ranges (0–0.1 m, 0.1–0.2 m, and 0.2–0.5 m) under RCP4.5, RCP8.5, and H+ scenarios. (The geographic coordinate system is ETRS89/UTM zone 31N.)

4.5.3. Implications for designing adaptation strategies

The approach adopted to assess the impact of RSLR in low-lying areas provides an alternative vision to considering the entire inundated surface as a total loss of value. The classical total damage approach results in management strategies based primarily on flood control. This is the case of the ED, where rice producers have developed an adaptation plan that includes building a dike along the bayside shorelines and at the back of beaches to prevent inundation of the deltaic plain and, thus, the inundation of rice fields (Comunitat General de Regants del Canal de la Dreta del Ebre, 2017). However, even where such a barrier is advantageous, rice fields within the potential inundation area are typically below future projected water levels and, consequently, will be severely affected by saltwater intrusion (e.g., Genua-Olmedo et al., 2016). Thus, to maintain their productivity, additional investment to adapt the existing hydrological infrastructure is also required, such as pumping systems to remove water from low-lying fields. In the case of the LD and GR, this strategy is not likely plausible given that the extent of habitats of economic interest is very small, unless the H+ scenario is considered. However, even in this extreme case, the damage is expected to be relatively low.

The adoption of an adaptation strategy based on protecting the anthropogenic system would artificially bind existing natural areas, such as lagoons and wetlands, disconnecting them from the sea, and further limiting accommodation space along the coastline. This implies a strategy based on poldering, although alternative nature-based strategies are increasingly being considered in areas that traditionally use this approach, including removing existing barriers to enhancing natural values (e.g., van Staveren et al., 2014; Wesselink et al., 2015). In fact, given there is no “silver bullet” solution to adaptation, a transformative change in current policies is needed that goes beyond the existing portfolio of accepted approaches (Suckall et al., 2018).

Addressing maladaptation in coastal areas may have devastating effects and, sometimes, may cause more damage than a “do nothing” approach in which nature is allowed to take its course (Hoggart et al., 2014). In areas of high environmental value, ensuring accommodation space for natural habitats to adapt may be a feasible strategy to cope with the effects of SLR (Haassnot et al., 2019). However, urban sprawl and the existence of flood-prevention structures can act as barriers that inhibit such dynamic ecosystem responses (Enwright et al., 2016). Promoting natural protection by creating natural buffer areas must be accompanied by the progressive removal of anthropogenic infrastructure that prevents migration, thus favoring ecosystem connectivity. This may be feasible in the ED because of its low elevation and flat topography, since landward migration of wetlands is largely controlled by the topographic slope of the adjacent upland (Kirwan et al., 2016). This could be achieved by reclaiming stretches of agricultural land located at the lowest elevations, which are the first to be affected by inundation and saline intrusion, to be transformed into wetlands and, in turn, restrict urban infrastructure and rice fields to higher elevations on the plain. This approach to managing inundations will result in a dynamic coastal landscape where habitats would shift according to future conditions and where the existing channel network could be used to control salinity. This strategy is not usually well received by local stakeholders set to be most economically affected (Ledoux et al., 2005; Myatt et al., 2003; Parrot and Burningham, 2008) in general, and in ED in particular (Fatorić and Chelleri, 2012; Roca and Villares, 2012). In the GR, potential social conflicts exist between different stakeholders in the context of environmental protection, largely as a result of perceived threats to agriculture (Roca et al., 2011). The existence of multiple stakeholders with different perspectives is always a challenge in adaptation planning, with “winners” favoring adaptation and “losers” opposing it (Hinkel et al., 2018). Nevertheless, the creation of new wetland areas may support alternative economic activities focused on environmental conservation, which could be more sustainable given the high environmental value of the area (e.g., birdwatching, cycling, eco-tourism, etc.) (Figueras et al., 2011; Sauri et al., 2010). Further understanding of the perceptions of all stakeholders is required during the design of sustainable adaptation actions in response to climate change (Fatorić et al., 2014). When addressing SLR-induced flooding in highly vulnerable areas, such as lowlands, quantifying affected areas as direct losses is justified assuming no change in the status quo; however, considering the inherent capacity of some coastal landscapes to adapt, SLR may present new opportunities. In Catalonia, wherever possible, promoting habitat creation may help increase coastal resilience in the face of SLR and provide additional ecosystem services in environmental hotspots, even where these are progressively degraded by human actions.

4.6. Conclusions

In this work, we have presented a methodology for improved SLR-induced inundation-damage assessments in natural coastal areas. To improve the delineation of inundation-prone areas, the classical bathtub approach was integrated with an equilibrium-based coastal response to RSLR to account for the dynamic adaptation capacity of sandy shorelines. To improve the assessment of induced damage in inundated areas, the likely ability of coastal habitats to adapt to changing conditions was simulated by linking their spatial distribution with their expected ability to respond to changing sea-level conditions. This methodology was applied to assess the impact of different scenarios of RSLR in the most vulnerable low-lying areas of Catalonia, which also have the highest natural values along the coast.

Obtained results showed a very different susceptibility of the study sites to inundation, being the ED the most affected one under all considered scenarios. In terms of associated impacts, the most affected habitat was croplands, which is unable to adapt to new conditions, and it will convert to natural habitats (wetlands/lagoons) depending on local hydraulic connectivity. In this sense, existing man-made infrastructures in the ED plain play a double role. On the one hand, the existing network of channels controls the inundation extent on the plain, and on the other hand, they act as physical barriers limiting the horizontal habitat migration and the formation of new natural areas.

The adopted approach permits to move beyond traditional inundation-damage assessments where any affected area is considered as a total loss of value. In areas of high natural values, this may lead to consider SLR not only as a threat but also as an opportunity for a change in their management that allows a range of adaptation strategies different from classic protection measures.

Chapter 5

Valuating the impacts of sea-level rise on the natural function

5.1. Introduction

In the previous Chapter, the impact of SLR on areas comprising most of the natural value of the Catalan coast was assessed by estimating the expected changes in the surface occupied by most important habitats under different SLR scenarios. In this Chapter, these changes are valued in monetary terms by evaluating which are the ecosystem services (ES) provided by such habitats and how they evolve in time. By definition, ES are the benefits human population derive, directly or indirectly, from ecosystems (Costanza et al., 1997). Estimating their economic value can be a useful to measure trade-offs between environment and society to enhance the human well-being in a sustainable manner.

Costanza et al. (1997) and Daily (1997), among others, were the pioneers on assessing the monetary valuation of ES, and since then, this approach has been widely used to value, in economic terms, natural areas that traditionally had not any market value (e.g. de Groot et al., 2012; Costanza et al., 2014). This has also boosted by international initiatives such as *The Millennium Ecosystem Assessment* (MEA, 2005), and *The Economics of Ecosystem and Biodiversity* (Van der Ploeg and de Groot, 2010).

The coastal zone comprises the most productive ecosystems, providing a range of social and economic benefits to humans yet being highly threatened systems (MEA, 2005). In fact, coastal environments may contribute with about 77% of the global ecosystem service value (ESV hereinafter) (Costanza et al., 1997) although their assessment is much more limited than of terrestrial ones (Barbier, 2012; Liquete et al., 2013) and, traditionally, their generated benefits have been generally ignored in environmental planning and decision-making. Nevertheless, by treating and accounting for coastal ES as an economic part of development infrastructure, natural assets may be comparable with other economic sectors when making investments and implementing management actions (Arkema et al., 2015; Marre et al., 2016; Waite et al., 2015).

In this sense, it is expected that a major driver such as SLR, which is likely to produce a change in the distribution and quality of natural assets along the coast, would also produce a significant variation in the associated flow of environmental services (Mehvar et al., 2019; Yoskowitz et al., 2016). As an example, it is well-recognized that SLR-induced losses and changes in wetland distribution (Craft et al., 2009; Traill et al., 2011, among others) would affect their provided ES such as disturbance regulation and recreational activities (Feagin et al., 2010; Gedan et al., 2011). Because the quantity and quality of ES are strongly linked to changes in the coastal landscape, modifications on environmental conditions may affect the systems' functionality and the provision of ES (Mitchell et al., 2013).

For the Catalan coast, Brenner et al. (2010) were the first to generate a baseline estimate of the economic value of the ES provided by ecosystems within coastal comarcas. They estimated a total value of about US $3,196 M (at 2004), although they mostly valued terrestrial habitats. Following their approach, Dupras et al. (2016) assessed the impact of changes in land use in the Maresme coastal comarca by estimating changes in ESV due to observed urban sprawl. These works highlighted the importance of accounting for non-market values of ES when designing spatial planning policies. In this aspect, Soy-Massoni et al. (2016) assessed the social perception of the multiple benefits provided by agricultural landscapes in Costa Brava by showing the need for a balance between productive goals and nature conservation.

Within this context, the main aim of this Chapter is to quantify potential SLR-induced variations in the ESV flow along the low-lying coastal areas analysed in the previous Chapter. By developing this ecological economic point-of-view, it is expected to provide a better insight into interactions between environment and economy, which would permit decision-makers to have an alternative view of induced SLR changes to make decisions on adaptation in natural areas.

5.2. Methodology

The methodology for this study comprises the following steps: (i) assignment of ESV for each habitat type; and (ii) assessment of the ESV flow for the SLR-induced changes in natural areas evaluated in the previous Chapter. This will be applied to habitat changes estimated by applying the two considered methods, total damage and conversion approach (TDA and CA), to compare the implications of the adopted one.

Before proceeding with the description of the methodological aspects, some remarks need to be made. Firstly, specific coastal habitats must be identified under a defined typology, which has been done in Chapter 4. However, it was a challenge to link ES to the defined habitat typology. Secondly, the definition of the study area is crucial for delimiting boundaries for ESV estimations. For the purpose of this study, the ESV will be estimated for the low-lying areas described in Chapter 4 (GR, LD and ED) since they are the most vulnerable to flooding and concentrate the areas comprising the highest natural value along the Catalan coast.

5.2.1. ESV for habitat types

The first step involves the definition of the ES to be assessed. Although there are different approaches to ES classification, we adopted the typology developed by Costanza et al. (1997) for standardization and comparability purposes. Moreover, following de Groot (2006), only those services that can be managed on a sustainable basis were included. Such ecological sustainability can be defined as "*the natural limits set by the carrying capacity of the natural environment (physically, chemically and biologically), so that human use does not irreversibly impair the integrity and proper functioning of its natural processes and components*" (de Groot et al., 2000). This excludes the integration of some production (e.g., food, raw materials, medicinal and ornamental resources) and carrier (e.g., cultivation, energy-conversion, mining, waste disposal, transportation) functions since they involve the conversion of original ecosystems into other unsustainable land use type. As a result of this, 14-non consumptive services provided by natural and semi-natural ecosystems are considered here (Table 5.1).

Table 5.1. Functions and services of natural and semi-natural ecosystems.

Ecosystem function	Ecosystem service	Examples
Regulation	1. Gas/climate regulation	C-sequestration
		Maintenance of air quality
		Maintenance of favourable climate
	2. Disturbance regulation	Flood prevention and control
		Storm protection
	3. Water regulation	Drainage and natural irrigation
	4. Water supply	Storage and retention of water
	5. Erosion control	Maintenance of arable land
		Deposition of nutrients
		Retention of soil
	6. Soil formation	Soil fertility
		Maintenance of soil structure
	7. Nutrient regulation	Nutrient cycling
	8. Waste management	Waste treatment
		Pollution control/detoxification
		Water purification
	9. Pollination	Biocontrol
		Seed dispersal
	10. Biological control	Trophic-dynamic relations
Habitat	11. Habitat and refuge	Nursery
		Living space for plants and animals
Production	12. Genetic resources	Genepool
		Biodiversity protection
Information	13. Aesthetic and recreation	Ecotourism
		Fishing
		Enjoyment of scenery
	14. Cultural and spiritual	Education
		Heritage value
		Science

Following the analysis of Brenner et al. (2010) in the Catalan coast, ESV are estimated by applying the transfer value method. The aim of this method is to assess the ESV of our study area using the results from previous original studies conducted in other areas (Loomis, 1992). It involves transferring the results of monetary estimates of ES from one location to another assuming socio-economic and environmental similarities between selected areas. Although there is still a great debate over the validity of this method (Brouwer, 2000; Johnston and Rosenberger, 2010), the practice of the value transfer for ES valuation is justified when primary data collection is no feasible due to any reason (Wilson and Hoehn, 2006), as is the case of the present study; being one of the most widely applied approach (Brander et al., 2012; Camacho-Valdez et al., 2013; Dupras et al., 2015, 2016; Liu et al., 2010).

The valuation of the ES of each habitat identified was carried out using the values obtained from the Ecosystem Service Valuation database (ESVD) (Van der Ploeg and de Groot, 2010). This is one of the largest open-access databases that includes ESV classified by biomes and ecosystems allowing for an easy retrieval for value transfer. Furthermore, to increase the robustness of this assessment, we used some estimates from the database of Brenner et al. (2010) who evaluated the non-market value of the ES provided by the Catalan coastal zone. Table B5 Annex B lists the studies that were used in this analysis.

The selection of values for the ES assessment was based on the following criteria: (1) areas with similar socio-economic and ecological characteristics to Catalonia, mostly Western Europe and North America; (2) non-market values related to non-consumptive resources; and (3) natural and semi-natural ecosystems similar to those defined in Chapter 4 (e.g., desert, coral reefs and tropical forests were excluded from the analysis).

Due to the lack of information on ESV for determined habitat types identified previously, two major assumptions were made: (i) coastal lagoons are often considered as a category of wetland (Enjolras and Boisson, 2010) and, consequently, are valued as such; and (ii) riparian landscapes are used for transferring the ESV to coastal and halophyte vegetation areas due to their spatial distribution and biophysical characteristics (Naiman and Décamps, 1997; Tabacchi et al., 1998). Both assumptions are based on functional affinities and available data for the development of the ES valuation.

To enable a direct comparison and aggregation of economic estimates of ES, values were standardized to a common currency, spatial and temporal units, namely euros per hectare per year (€/ha·yr). Then, values were adjusted to 2020 using GDP deflators using appropriate conversion factor from the National Statistics Institute (INE, 2020).

Finally, we calculated the average value for each ESV within each habitat type. Due to the scarcity of values in some categories, a simple statistical analysis was done by calculating the standard deviation, the median, minimum and maximum values provide insight into the distribution of the values.

5.2.2. ESV flow

The total ESV annual flow for a given habitat is calculated by integrating the provided individual ESV following the Eq. 5.1, where $V(ES_i)$ is the flow expressed in currency amount per year units, $A(LU_i)$ is the surface of habitat type (i), and $V(ES_{ki})$ is the annual value per each ecosystem service (k) generated by habitat type (i) (Troy and Wilson, 2006).

$$V(ES_i) = \sum_{k=1}^{n} A(LU_i) \times V(ES_{ki}) \tag{5.1}$$

As it was seen in Chapter 4, habitats located in the intertidal zone are the most likely to suffer potential changes in their eco-morphological characteristics due to RSLR, and as a consequence, those which provided ES are most likely to change (Mehvar et al., 2019). As an example, coastal wetlands being subjected to submersion (i.e. transitional wetlands) will experience a significant salinity increase leading to a change in dominant plant communities (Day et al., 2000; McKee et al., 1989). Furthermore, mainly in the ED, a large part of coastal lagoons will be saltwater semi-enclosed ones instead of closed lagoons as they are under current conditions. Therefore, provided ES may differ from the current ones in such a way such potential impact must be introduced on ESV flow estimations. To mimic this change, a reduction factor will be applied to original ESV values. In this work, it is assumed a reduction in present values of 75% and 10% for transitional wetlands and lagoons, respectively. Higher resilience on coastal lagoon areas is considered since water characteristics on these new areas could be modulated by freshwater inputs through irrigation channels, if desired. The assignation of these values is arbitrary since there is no data for different sub-habitats generated. In order to address the associated uncertainty, a brief sensitivity analysis will be presented in the Discussion section.

With respect to the contribution of beach and dunes on ESV flow, this work only considers those functions not related to recreational uses since the value of this service is highly dependent on the original site characteristics (e.g., attractiveness of the site, typology of users) (e.g. Lozoya et al. 2014); in such a way extrapolations of recreational values from other sites should be made with caution (Ariza et al., 2012). The importance of this function can be guessed by considering results obtained in the analysis of the impact of SLR on the recreational use of beaches along the Catalan coast (see Chapter 3).

Finally, estimations on ESV flows were projected to 2050 and 2100 under selected SLR scenarios assuming a zero discounting rate, meaning that the current value of money would be the same as that in future. Applying discounting rates from natural assets is a controversial issue (Azar and Sterner, 1996) on which there is still debate about whether discounting is appropriate at all or whether a non-constant rate should be assumed over time. Furthermore, such application is not relevant for comparative purposes, as in this case.

5.3. Results

5.3.1. Non-market value of ES

Table 5.2 presents the results from cross-referencing ES against defined coastal habitats. Grey cells represent potential ES provided by the feature, and blank ones indicate that the ES is not significant at the given habitat or, that it has not been documented. In addition, dark shading indicates the ES assessed in this work to be relevant for the Catalan coast, whereas light shading indicates that ES are expected to be provided by a habitat type (i.e., found in the literature) but it is registered in areas with different socio-economic or ecological characteristics than the Catalan coast.

Table 5.2 clearly shows how some habitats provide a larger number of services when compared to others. On the one hand, temperate forest, wetlands and coastal vegetation are the most productive habitats providing almost totality of identified ES. On the other, beach and dunes and urban greenspace provided few services although with a high value (see next Section). Nevertheless, all habitats are relevant for the functionality of the coastal system by providing complementary services.

Besides natural systems, converted habitats (e.g., croplands) can play an important role in the delivery of ES. In fact, cultivated farmland (croplands, pastures, orchards) are recognized to be a service-providing ecosystem (MEA, 2005; Power, 2010). Conversely, barren and salt mine areas are not expected to provide any ES or its value has not been found in the literature review. For the case of urban areas, it has been distinguished the urban greenspace including urban parks and other green areas that are able to provide a range of ES (Bolund and Hunhammar, 1999).

Table 5.2. Identification of ES provided by different habitat types (adapted from Brenner et al. (2010)).

	1. Gas/climate regulation	2. Disturbance regulation	3. Water regulation	4. Water supply	5. Erosion control	6. Soil formation	7. Nutrient regulation	8. Waste management	9. Pollination	10. Biological control	11. Habitat/refugia	12. Genetic resources	13. Aesthetic and recreation	14. Cultural and spiritual
Urban greenspace														
Barren														
Salt mine														
Cropland														
Grassland														
Temperate forest														
Beach and dunes														
Coastal vegetation														
Wetland														
Coastal lagoon														

A summary of economic value estimates for each habitat type is presented in Annex B, Table B6. Although the value transfer method is a crude first approximation at best,

Table B6 shows the ranges on these figures providing insight into the large variability of values. We found that the greater number of studies focused primarily on temperate forest (81 estimations) and coastal wetland areas (37 estimations). In terms of ES, the most valued were aesthetic and recreation (66 estimations) and gas and climate regulation (47 estimations) (see Tables B5 and B6).

Overall, beach and dunes was the most valued habitat (116,041 €/ha·yr) followed by coastal wetlands (19,903 €/ha·yr). Even, when the aesthetic and recreation service is removed as mentioned above, beaches and dunes remain as the most valued (75,163 €/ha·yr). This is due to the large value given to the disturbance regulation service. In contrast, the habitat types with the lowest total ESV were grassland (503 €/ha·yr) and cropland (2,781 €/ha·yr). It is important to highlight that the current analysis is focused on non-market values and provisioning services (e.g., food and raw material) provided by agricultural and pasture land were excluded (Table 5.3).

Total values by ES also reveal considerable variability. Disturbance regulation is the largest valuable ES (75,988 €/ha·yr) followed by aesthetic and recreation (53,194 €/ha·yr). For both ES, beach and dunes play an important role contributing 99% and 77% to their total ESV. This fact highlights that these habitats are essentially valued in terms of protection and recreation. On the other side of the spectrum, water regulation and genetic resources are the least valuable ES (23 €/ha·yr and 68€/ha·yr, respectively) (Table 5.3). Nutrient regulation was not be valued in this work since data found for this service do not follow the adopted criteria, with the scarce registered values are given in global terms and for large biomes such as continental shelf, coral reefs and seagrass beds (which are not considered in this work). We must stress that only relevant ES provided by coastal “terrestrial” habitats are valuated in this work.

Table 5.3. Non-market value of ES provided by each habitat type (values in €/ha·yr, 2020 price levels). *Aesthetic and recreation value for beach and dunes is not considered for presented estimations on ESV flow.

	Gas regul.	Distur. regul.	Water regul.	Water supply	Eros. contr.	Soil forma.	Nutrie. regul.	Waste manag	Pollin.	Biolog .cont.	Habit. refugi	Genet. resour	Aesth. Recr.	Cultur. Spirit.	Total ESV
Urban greenspace	926		17										5,863		6,806
Barren															
Salt mine															
Cropland					120	278			21	35	2,286		41		2,781
Grassland	102		6		74	9		95	36	33			148		503
Temperate forest	157			447	136	13		55	446	6	2,540	68	307	2	4,177
Beach and dunes		75,097											40,878*	66	116,041
Coastal vegetation		242		2,438									1,625	11	4,316
Coastal wetlands		649						13,777			649		4,332	496	19,903
Total	1,185	75,988	23	2,885	330	300		13,927	503	74	5,475	68	53,194	575	154,527

5.3.2. ESV flow in natural low-lying areas

Projected annual flow of non-market value of ES for each habitat type by 2050 and 2100 under tested scenarios are given in Tables B7, B8 and B9 for GR, LD and ED, respectively. At current conditions, it is estimated that ES contributed annually €45.0 M, €21.6 M and €287.8 M to the total natural capital of GR, LD and ED, respectively (Fig. 5.1). To put in context the much higher flow provided by the ED, it is necessary to consider that in addition of the different representation of habitats, it has the largest extension (i.e., the analyzed extension in the ED is approximately 4 and 8 times larger than GR and LD, respectively).

Figure 5.1 shows the evolution of ESV flow under given SLR scenarios for the expected habitat distribution in each site estimated using the two approaches followed to assess the SLR-induced impact based on the likely conversion (CA) and the total damage (TDA) on habitats.

Under the CA, the likely conversion of some habitats entails a variation in their ESV flow which is highly dependent on specific characteristics of each site. In GR and LD, changes in ESV flow are relative smaller under both RCP scenarios since SLR-induced changes are limited to the external coastal fringe (i.e., beaches). Reductions in current ESV flow by 2050 will be less than 5% contributing annually €44.3 M and €20.6 M respectively (Fig. 5.1). Conversely, current ESV flow in ED will be maintained or even increased since estimated SLR-inundation resulted in a large expansion of natural habitats, mainly coastal wetlands and lagoons. Under RCP8.5, the projected ESV flow in ED will be €277.6 M/yr and €412.8 M/yr by 2050 and 2100, respectively, representing 96% and 143% of its current ESV flow (Fig. 5.1).

As expected, the most noticeable changes in ESV flow are calculated under the H+ scenario. Despite having a great impact in terms of affected surface, a positive effect on natural assets is predicted due to the high value of new natural areas to be generated through inundation. This is clearly observed at longer-time projections (by 2100) at which ESV flow in GR and LD is projected to be approximately 50% higher than current conditions contributing €65.2 M/yr and €32.5 M/yr, respectively. By far, the largest increase is found in ED due to the largest naturalization of the area in such a way the ESV flow will be increased by 81% delivering €520.8 M/yr to society (Fig. 5.1).

However, reductions in ESV flow would be expected if habitats shifts were not considered and coastal habitats were projected to decrease in size and their corresponding ESV. By 2050, considering RCP8.5 as a reference, the natural value in GR and LD will decrease roughly to 94% of current values (€41.8 M/yr and €20.3 M/yr, respectively) whereas it will be further reduced in ED maintaining only the 61% of its current natural value (€175.3 M/yr). When the analysis is extended to 2100, the decrease on ESV flow will be more evident in ED than in the other two areas maintaining only 19% of the current values under RCP8.5 (€55.0 M/yr). Despite this, the ESV flow in ED will be approximately 2 times higher than GR and 3 times higher than LD, whose ESV flow will be €31.4 M/yr and €16.8 M/yr, respectively (Fig. 5.1).

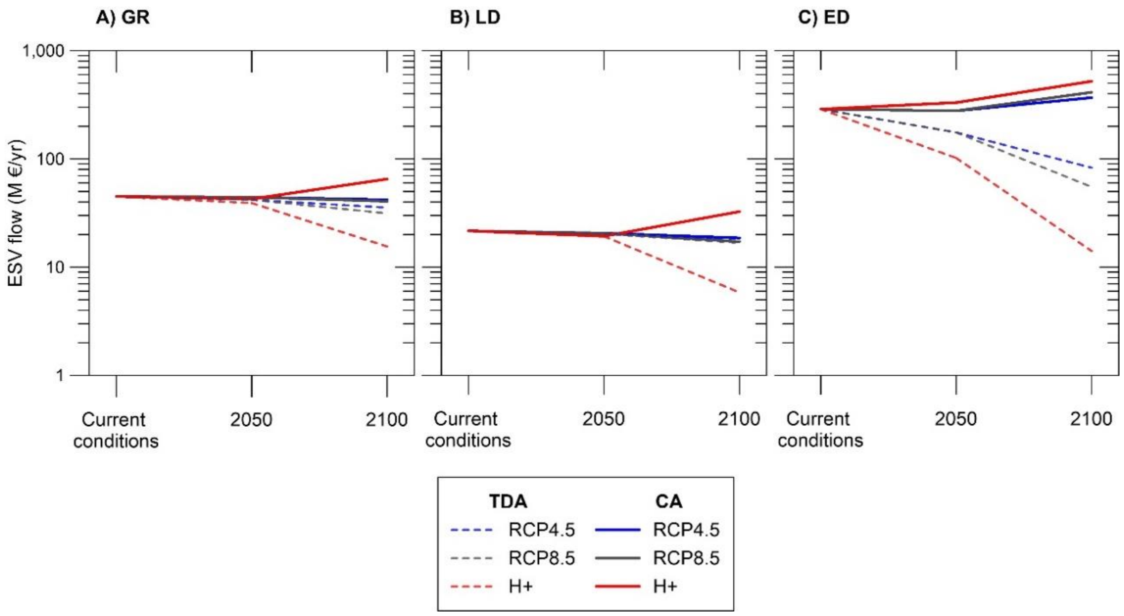


Figure 5.1. Projected ESV flow for a) GR; b) LD; and c) ED considering TDA and CA at different SLR-scenarios.

With respect to the proportion of each coastal habitat to the total ESV flow (Fig. 5.2), the most productive are coastal wetlands, beach and dunes and croplands. Their largest contribution is due to these natural ecosystems were the most valued (i.e., the highest total ESV in this work) and the substantial representation of cropland areas in the total study area. The contribution of these habitats under current conditions represent the 90%, 77% and 79% of the total value in GR, LD and ED, respectively (Fig. 5.2). For croplands, its proportion to the total ESV will increase in the three study areas under RCP8.5 by 2100 by considering the TDA whereas it will be reduced by the CA, especially in the ED. In the case of wetlands, its contribution to the total ESV will remain very similar in both approaches at GR and LD but it will decrease in ED being practically null under the CA. The great difference is observable in the contribution of coastal lagoons that will be decreased in the TDA but highly enhanced in CA.

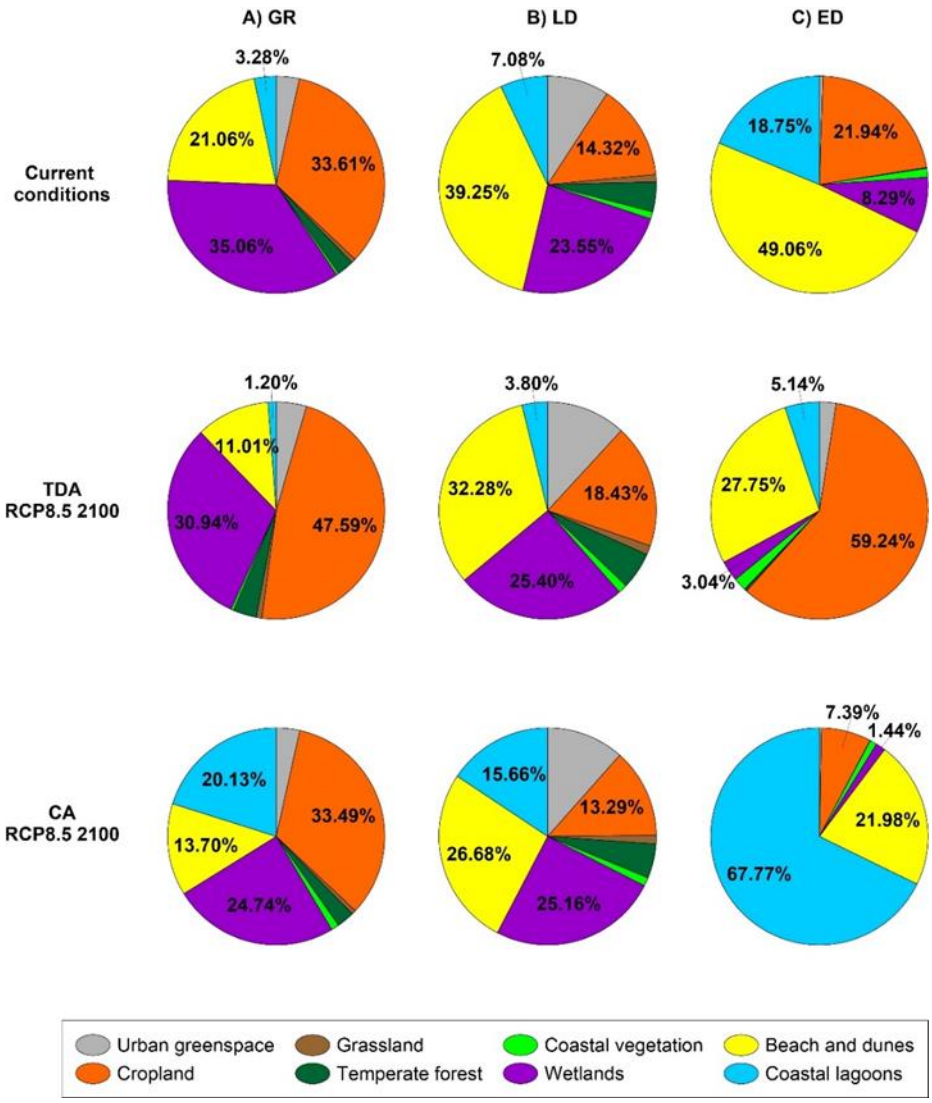


Figure 5.2. Contribution (in %) for each habitat type to the ESV flow for a) GR; b) LD; and c) ED considering TDA and CA.

5.4. Discussion and conclusions

5.4.1. Methodological aspects

In this work, we have adopted the transfer value method which has been widely used in similar analysis (Brenner et al., 2010; Dupras et al., 2015, 2016; Liu et al., 2010; among others), despite being also subjected to debate in the environmental economic literature (e.g. Brouwer, 2000; Johnston and Rosenberger, 2010). However, under the absence of local values for ES, it is the only remaining option. In this respect, there are some elements to be considered to put in context the obtained results. Firstly, not all ES provided by coastal habitats have been well studied, and others even have not been consider at all. Ideally, updated and broad assessments on ES are need to fill the gaps in the literature to provide a more complete coverage of services provided per each ecosystem that would almost increase the total ESV. Consequently, the estimated figures underestimate the actual value of ES provided, and the estimated value should be considered as the minimum value.

Another major limitation stems from the plurality of classification of ES in the literature. Several ES classifications have been proposed (Costanza et al., 1997; de Groot et al., 2002; Farber et al., 2006) which introduces some noise when they are used for ES assessment. Furthermore, characterizing certain services is a difficult task (e.g., erosion control, nutrient regulation) because the value is not easily transferable, or available data do not exist (Barbier et al., 2011). In agreement with previous studies (Brenner et al., 2010; de Groot et al., 2012) the categories of disturbance regulation and aesthetic and recreation were the most valued ES (both in the number of estimates and the value obtained).

Despite these challenges, integrating climate change and ES assessment is vital. SLR-impacts may alter the coastal ES in a different way depending on the ecosystem type and provided services (Mehvar et al., 2018). In this work, one of the most important changes is associated to the ES provided by coastal wetlands (including coastal lagoons), due to its expansion but also due to the expected shift in their composition towards more salt-dominated environments. Although scarce, recent studies have quantified variations in the value of coastal ES (Roebeling et al., 2013; Yoskowitz et al., 2017) but they have not explicitly quantified the change in the ESV (Mehvar et al., 2018). In order to test the sensitivity of modifying the ESV provided by coastal wetlands to changing eco-physiological conditions, different reduction rates were applied and compared as there is no available data for new sub-habitats generated (Fig. 5.3). Considering RCP8.5 by 2100 as a reference, the ESV flow would be €41.8 M/yr, €17.4 M/yr and €425.5 M/yr for GR, LD, and ED, respectively, if no reduction were considered. Presented results in this work assumed a reduction of 75% in ESV due to expected change in eco-physiological conditions, so that the ESV flow was reduced by approximately 3% in GR and ED and 1.5% in LD. As expected, the smaller change in provided services, the smaller variation in the projected ESV flow. As an example, considering a moderate change in environmental conditions (50% reduction in provided ES), the ESV flow would decrease by 2% in GR and ED (€41.0 M/yr and €417.0 M/yr, respectively) and 1% in LD (€17.3 M/yr). If provided services changed slightly (5% reduction in ESV), no major changes would be observed in its contribution whose reduction in the ESV flow would be less than 0.25%. These results stress the need to know how habitats evolve and to assess the differences in ESV for each habitat type.

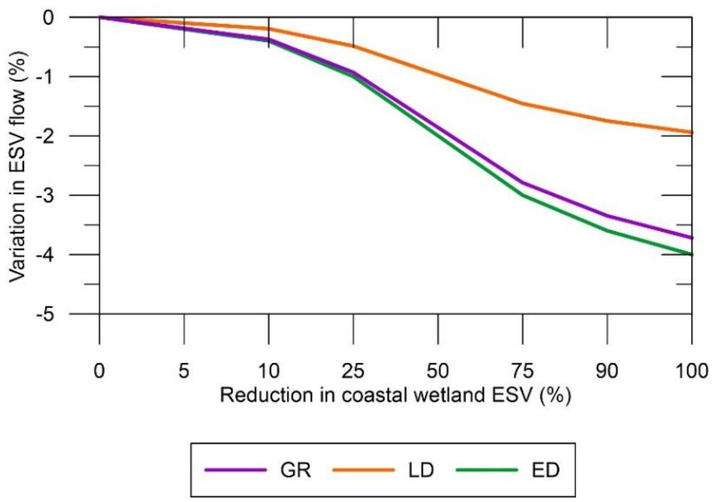


Figure 5.3. Variation in projected ESV flow (in %) for RCP8.5 by 2100 considering different reduction rates on provided ES by coastal wetlands.

Other important aspect to be considered is the existing lack of information for certain habitats. As an example, coastal lagoons are underrepresented across valuation studies (Barbier et al., 2011; Newton et al. 2018), with valuation of their ES being based in few studies (e.g., De Wit et al., 2015; Rolfe and Dyack, 2010). The limited number of studies and different approaches to define coastal lagoon systems make difficult to find "reliable" valuation studies (Camacho-Valdez et al., 2013). To overcome this, the ESV of lagoons was taken as the ones from coastal wetlands since, following the Ramsar classification; they include permanent shallow marine waters with less than six meters deep. Such characteristics represent the coastal lagoon areas found in the study areas. A similar approach was adopted for areas with coastal and halophyte vegetation. There is no specific valuation for these habitats and, thus, we decided to use estimations from riparian vegetation areas. Riparian zones are an interface between terrestrial and aquatic ecosystems with ecologically rich habitats supporting a number of ES (Dosskey et al., 2012, Stutter et al., 2012). The observed coastal and halophyte vegetation areas in the study areas are found near or above HSL fitting into the operational definition of marine riparian plants (Levings and Jamieson, 2001).

5.4.2. Economic consequences on natural areas along the Catalan coast

According to obtained results, natural environments in the Catalan coast, mostly found in low-lying areas, generate a significant economic value when considering their ES contribution to human well-being. Among the analysed areas, the ED is the most productive area delivering at current conditions €287.8 M/yr to society. Such contribution is approximately 6 and 13 times higher than the ESV flow of GR and LD, respectively. To identify which part of this difference is associated with their extension, these values have been normalised by their respective surface (Fig. 5.4). As it can be seen, the most valuable area is the ED with an average ES of 8,675 €/ha·yr. GR and LD present similar values of 5,287 €/ha·yr and 5,118€/ha·yr, respectively. This implies that the natural value per hectare of ED is about 1.7 times higher than in the other two areas. Under the RCP8.5 scenario, the relative ESV flow of these areas slightly decreases by 2050, although maintaining their relative contribution, with 5,207 €/ha·yr, 4,873 €/ha·yr, and 8,369 €/ha·yr for GR, LD and ED, respectively. However, the large habitat conversion expected in the ED by 2100, with its corresponding increase in ESV flow up to 12,444 €/ha·yr, makes that its relative value in comparison to GR and LD will be 2.6 and 3.1 times higher, respectively.

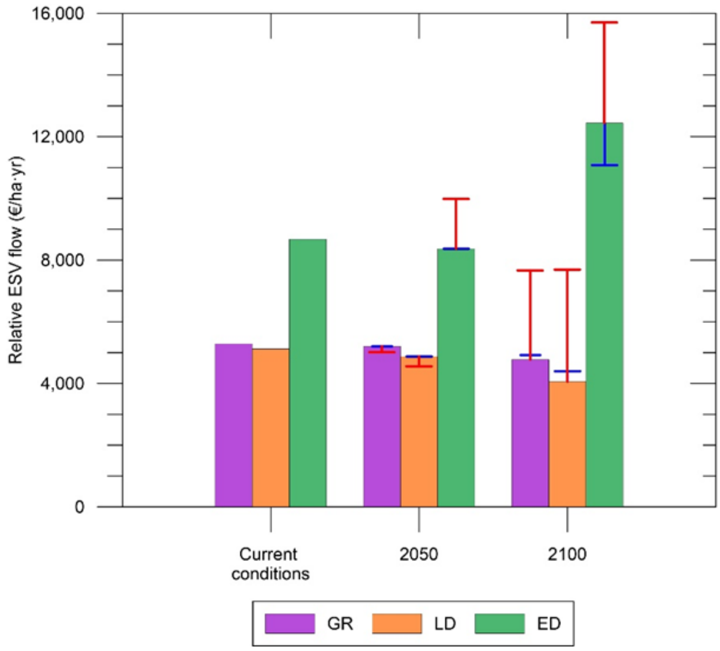


Figure 5.4. Relative annual flow (€/ha·yr) for the different analyzed areas considering the CA. Note: for 2050 and 2100 projections, bars represent values under RCP8.5 scenario. Blue and red error bars represent the range of values by considering RCP4.5 and H+, respectively.

As mentioned before, the aesthetic and recreational service provided by beaches was not included because its assessment applying the value transfer method should be made with caution (Ariza et al., 2012). Most estimates of this service are based on the "willingness to pay" (WTP) (e.g., hedonic pricing, travel cost, contingent valuation methods) which are conditioned by human preferences and knowledge base. A study carried by Lozoya et al. (2014) in Costa Brava showed that the WTP in protected natural areas is higher than in urban beaches, which is highly dependent on the user profile. This may be related to the quality of the surrounding areas and the perception of the beach users (Roca and Villares, 2008). In spite of this, an alternative "number" representing this ES can be obtained by considering the impact of coastal tourism on the GDP of the Catalan coast (Chapter 3), which on average it corresponded to €16 M/beach hectare. However, this figure does not only include the value of the beach, but also associated recreational services for beach exploitation and use. With the exception of Barcelona, the largest contributions to the economy per beach hectare were found in Costa Brava and Costa Dorada with €20.8 M and €14.1 M, respectively. Conversely, beaches in ED only contribute €1.6 M per hectare showing its secondary recreational use under current recreational and tourism planning.

5.4.3. Concluding remarks

This study showed the non-market estimations for the main natural areas located along the Catalan coast using the value transfer approach where SLR-impact on the value of ES provided by coastal habitats has been assessed at mid- and long-term projections. Results indicate that the ED is the most valuable area delivering at least €288 M/yr to society nowadays, which is approximately 6 and 13 times higher than in GR and LD, respectively.

Besides increasing the coastal resilience in the face of SLR as seen in the previous Chapter, our results indicate that promoting habitat conversion will maintain and even enhance the benefits provided by coastal ecosystems. The ESV flow in GR and LD will remain almost the same along this century since these areas are less vulnerable to SLR-inundation with changes limited to the external coastal fringe. However, due to the largest naturalization and habitat shift expected in ED, the ESV flow in this area will be roughly doubled by 2100, mainly due to the creation of new coastal lagoon areas that will be able to provide valuable ES for human welfare and well-being.

In the context of EU Biodiversity Strategy for 2030, this work highlights the need to recognize and value the equivalent economic contribution of natural areas to society which can lead to a shift in the management perspective promoting their conservation and protection in future management strategies. In future adaptation policies, allowing for habitat conversion should take precedence over land reclamation and protection for economic purposes wherever possible, putting the biodiversity on a path to recovery with multiple benefits for people and the climate.

Adaptation to climate change

Chapter 6

Financing and implementation of adaptation measures to climate change along the Spanish coast

Adapted from: López-Dóriga, U., Jiménez, J.A., Bisaro, A., Hinkel, J. 2020. Financing and implementation of adaptation measures to climate change along the Spanish coast. Science of the Total Environment, 712, 135685. doi: 10.1016/j.scitotenv.2019.135685

6.1. Introduction

Climate adaptation has become a core focus in the political agenda, with the goal of enhancing preparedness and the capacity to cope with climate change impacts (Biesbroek et al., 2010; Khan and Roberts, 2013). Indeed, EU Member States have started to develop national adaptation strategies requiring physical, social, and institutional measures to adapt to climate change, given the recognition that mitigation alone is insufficient to prevent impacts (Biesbroek et al., 2010).

While adaptation strategies to climate change are necessary everywhere where significant impacts are expected, coasts are areas of special interest since they concentrate a series of characteristics related to their susceptibility to natural hazards, their exposure in terms of natural and human values, and the fact to be directly subjected to one of the most relevant climate-related changes, the accelerated rise in sea level (see e.g. Nicholls et al., 2007). As a consequence, coastal communities and infrastructures are likely to be affected and, therefore, coastal adaptation will be required on almost all populated coastlines in the world (Nicholls, 2011). In fact, the European Climate Change Adaptation Strategy recognises coastal areas as one of the most at risk being priority areas to climate change adaptation (European Commission, 2013). In this sense, many studies state that adaptation costs would be lower than damage costs without adaptation for most developed coasts. As an example, the economic cost of coastal flooding has been estimated at €18 billion under a scenario of 50 cm of sea level rise, but adaptation may significantly reduce changes to €1 billion/year (EEA, 2008). These issues are not limited to Europe, without adaptation, 0.2–4.6% of the worldwide population is expected to be flooded annually in 2100 under 25–123 cm of global mean sea-level rise, with expected annual losses of 0.3–9.3% of the global gross domestic product (Hinkel et al., 2014).

In spite of this, although numerous studies on coastal adaptation have been performed in recent years, most of them have focused on mapping the current state of adaptation plans (e.g. Araos et al., 2016; Gibbs, 2019; Pearce et al., 2018; Woodruff and Reagan, 2019), while a noticeable lack of studies on the implementation of adaptation does exist (e.g. Mimura et al., 2014). Moreover, governments at all levels are expressing their intention to adapt, but not much progress is being made in terms of implementation (Berrang-Ford et al., 2011). One possible explanation is that the associated political risk of adaptation could act as a constraint (Ford et al., 2011; Gibbs, 2016; Lesnikowski et al., 2015). In fact, a review on early implementation of adaptation plans by local governments has shown that they mostly adopt a reactive or event-driven approach, with a main focus on climate variability and current weather extremes rather than long-term climate change (Mimura et al., 2014).

Furthermore, there is an increasing recognition that barriers to coastal adaptation are not technical or economic, but are largely financial and social (Hinkel et al., 2018). Indeed, while an adaptation finance gap is substantial across all sectors (UNEP, 2016), it is significant for coastal adaptation in particular, where currently, governments appear to be meeting only a fraction of the costs needs to ensure flood safety (Nicholls et al., 2019). Financing coastal adaptation is challenging for several reasons. First, coastal adaptation provides long-term stochastic benefits, whereas the costs of provision are large and upfront (Bisaro and Hinkel, 2018), putting pressure on strained public budgets that need to consider opportunity costs of investment (Penning-Rowsell and Priest, 2015). Second, coastal adaptation involves high-value coastal real estate, and adaptation measure values can affect amenity values, for example, sea walls may decrease the quality of ocean views, giving rise to rent-seeking behaviour by vested interests in blocking such measures (Beatley, 2012). Third, coastal areas are subject to multiple uses and diverse stakeholder interests. The resulting governance structures often result in overlapping or unclear public responsibilities (Storbjörk and Hedrén, 2011), which act as a barrier to financing. Yet while the current literature has described and enumerated such barriers, often in individual case studies (Eisenack et al., 2014), less attention is dedicated to analysing coastal adaptation financing decisions at the national level to, for example, identify patterns in such decisions and the underlying drivers of such barriers. Therefore, a better understanding of the adaptation finance is necessary to better tailor appropriate solutions, as the overall expenditures for coastal adaptations will rise with the sea level, and must compete for resources with other concerns (Moser et al., 2018). As a consequence of all this, it seems clear that coastal adaptation needs to start earlier than anticipated to provide time to engage stakeholders, to enable effective decision making and to implement measures (Haasnoot et al., 2019).

Within this context, Spain adopted the National Adaptation Plan to Climate Change (PNACC) and the Spanish Strategy for Coastal Adaptation to Climate Change (CAS hereinafter) in 2006 and 2016, respectively. This is a statutory and multi-sectorial national planning strategy for climate change adaptation of coastal areas, with the aim of assisting in the decision-making process to plan for, implement and monitor adaptation actions (Losada et al., 2019). Thus, since Spain is starting to implement coastal adaptation actions, the assessment of these early-stage investments is important to put them in the context of long-term coastal planning. In this sense, it has to be considered that most of climate adaptation efforts reported worldwide deal with partial solutions and approaches to climate adaptation, rather than more full-scale implementation (see Mimura et al., 2014).

Understanding coastal adaptation financing and implementation provides context for this paper, where the case of Spain is particularly interesting since it is considered as one of the top countries in Europe in terms of climate adaptation initiatives as well as in investments in coastal protection in general (Policy Research Corporation, 2009a; Lesnikowski et al., 2015, 2016). Thus, it will be relevant to assess to what extent the implemented measures are consistent with the established policy goals and plans. In the absence of an approved roadmap to implement measures included in the CAS, it is worthy to identify the existence of a rationale behind the spatial distribution of investments at this early stage. As previously mentioned, Mimura et al. (2014) concluded that many early implementations of adaptation plans have a main focus on climate variability and extremes rather than long-term climate change. In this context, it is also relevant to assess if current implementation measures along the Spanish coast are really adaptation measures, or their targets are current coastal problems but financed under the umbrella of adaptation financing initiatives (PIMA-Adapta) as a matter of opportunity. This should be noted in the time evolution of total investments in coastal protection in the near future.

To our knowledge, no previous studies have provided an in-depth analysis of current investments in coastal adaptation measures for climate change at national level in general, and along the Spanish coastline in particular. Therefore, the main goal of this paper is to assess the current progress of Spain in implementing coastal adaptation measures to climate change. To this end, we have analysed how Spain is currently financing coastal adaptation; which measures within the CAS are currently being implemented; the extent to which measures already implemented are actually adaptation measures; and how the current investments in coastal adaptation measures compare with the occurrences of current "regular" coastal protection measures (without climate change). Finally, based on this analysis, we will provide policy recommendations on possible adjustments and the investment pattern required for an efficient long-term implementation of adaptation measures for climate change along the Spanish coast.

6.2. Study area

6.2.1. Study area

The Spanish coastline (Fig. 6.1) is approximately 7,900 km long, and comprises a high diversity of coastal environments including cliffs, rocky coasts, embayed beaches, long beaches, estuaries, swamps, dunes and deltas, along three main climate areas (Mediterranean, Temperate-Atlantic, Subtropical-Canary Islands). In general terms, the Mediterranean area has the largest abundance of beaches, whereas the Atlantic area presents the largest extension of cliff areas.

From an administrative standpoint, this coastline extends along 10 autonomous communities and 2 autonomous cities, comprising 20 coastal provinces and 487 municipalities. Approximately 40% of the Spanish coastline is urban, 7% is occupied by port facilities, 3% is occupied by industrial facilities and 8% is used for farming (Orts, 2016). The Spanish coast is also an area of high concentration of population, with approximately 45% of the national population living in coastal municipalities, which only represent approximately 7% of the territory. Table 6.1 shows an overview of the main physical and socioeconomic indicators of the Spanish coastal zone.

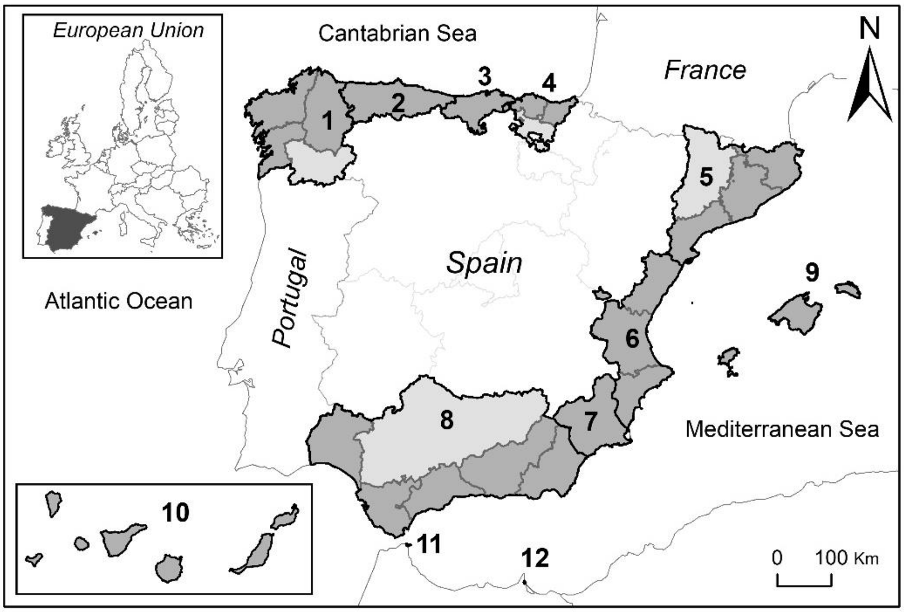


Figure 6.1. Coastal regions in Spain (see names in Table 6.1).

Table 6.1. Key statistics for Spain's coastal regions (data from National Statistics Institute (INE), 2015). Coastal GDP and population only consider information from coastal provinces within each region (dark grey areas in Fig. 6.1).

Region	Coastal length (km)	Coastal GDP (millions €)	Coastal population (inhabitants)
Galicia (1)	1,498	50.15	1,425,745
Asturias (2)	401	21.22	1,075,279
Cantabria (3)	284	12.20	566,678
Basque Country (4)	246	55.00	1,829,822
Catalonia (5)	699	193.35	6,595,767
Valencia (6)	518	100.77	4,692,449
Murcia (7)	274	28.21	1,335,792
Andalusia (8)	945	85.05	4,591,231
Balearic Islands (9)	1,428	27.34	983,131
Canary Islands (10)	1,583	40.92	1,968,280
Ceuta (11)	20	1.59	75,276
Melilla (12)	9	1.46	65,488

The combination of a long coastline, where inundation and erosion-induced problems are already frequent under current climate conditions (e.g. Del Río et al., 2012, 2013; Jiménez et al., 2012; Jiménez and Valdemoro, 2019; Rodríguez-Ramírez et al., 2003; Sanjaume and Pardo, 2005) and high human pressures concentrating values along the coast, makes the Spanish coastline a vulnerable environment to climate change-induced flooding and erosion. Nevertheless, coastal vulnerability significantly varies along the territory as a function of physical and socioeconomic characteristics. A national assessment of the expected impacts induced by climate change along the Spanish coast is given by Losada et al. (2014), who found that coastal systems were especially sensitive to the effects of sea-level rise and other factors such as rising water surface temperatures, acidification, and changes in storm surge. The obtained results have been used by the Spanish Office of Climate Change (OECC) to identify adaptation needs in the Spanish coastline as well as the required actions. Additional site specific assessments of sea level rise-induced impacts along the Spanish coasts can be found in Enríquez et al. (2017), Jiménez et al. (2017), López-Dóriga et al. (2019), Martínez-Graña et al. (2018), Toimil et al. (2018), among others.

6.2.2. Administrative framework for coastal risk and climate change adaptation

Formally, in Spain, the OECC holds the competences in adaptation to climate change policy-making, assessment, and implementation at the national level, among other climate change-related issues. These aspects included in the responsibilities of the Secretary of Environment within the Ministry for the Ecological Transition (MITECO hereinafter, formerly Ministry of Agriculture and Fisheries, Food and Environment).

In 2006, OECC developed the PNACC, which is the framework for coordinating the Spanish public administration to carry out actions to evaluate the impacts, vulnerability, and adaptation to climate change in Spain (OECC, 2006). This plan is implemented through work programmes, where priority activities to be addressed are covered. The current programme (WP3) was adopted in 2013 (OECC, 2014).

Competences on management in the coastal zone in Spain are distributed between different administrations, i.e. central government, autonomous communities and municipalities, with the central government playing the most important role. The autonomous communities have the administrative competence for urban planning in the coastal zone, whereas the national General Directorate for Sustainability of the Coast and the Sea (DGSCM hereinafter) is the administrative body for ruling and managing the maritime-terrestrial public domain. The DGSCM lays out and implements the coastal management policy that is applied in situ by their administration's peripheral services, known as coastal demarcations, to address identified coastal problems/issues along the Spanish coast. Thus, the central government has the competences in coastal protection along the entire Spanish coast and, in this sense, the funding for coastal protection is provided through the DGSCM.

With regards to the coastal zone, as a result of one of the obligations of the Law 2/2013 for the protection and sustainable use of coasts and amendment of the Spanish Coastal Act 22/1988, the DGSCM developed the Spanish Strategy for Coastal Adaptation to Climate Change (CAS hereinafter, as mentioned above). This national strategy was officially approved after a positive strategic environmental assessment in 2016 (DGSCM, 2016). It indicates different degrees of coastal vulnerability and risk along the entire Spanish coastline, and it identifies measures to address potential effects (Losada et al., 2019). This strategy is being downscaled to the regional level by developing specific strategies for coastal regions, in a process controlled by autonomous regions. In addition to this, the DGSCM has also developed several (five already done, two in progress) dedicated strategies to the protection of the coast in areas currently experiencing large erosion problems. These strategies diagnose the problem, prioritise areas to be protected, and propose different alternatives to address the problem, which are in line with measures considered in the CAS.

6.3. Material and methods

6.3.1. General methodological framework

As it has been already mentioned, the lack of comprehensive studies about implementation of adaptation measures at large scale, the characteristics of the information to be analysed, and the type of data to be analysed have driven us to design a methodological framework to be used in the analysis. The practical goal of the methodology is to get a country profile on the implementation of coastal adaptation measures. The proposed methodological framework serves to answer different questions contributing to get such profile and it is schematised in Figure 6.2. It consists of three main steps: (i) the creation of a database on implemented adaptation measures; (ii) the compilation of data to characterize regions where we are adapting and to describe the context of current investments in coastal protection; and (iii) the analytical module where data are analysed to answer target questions.

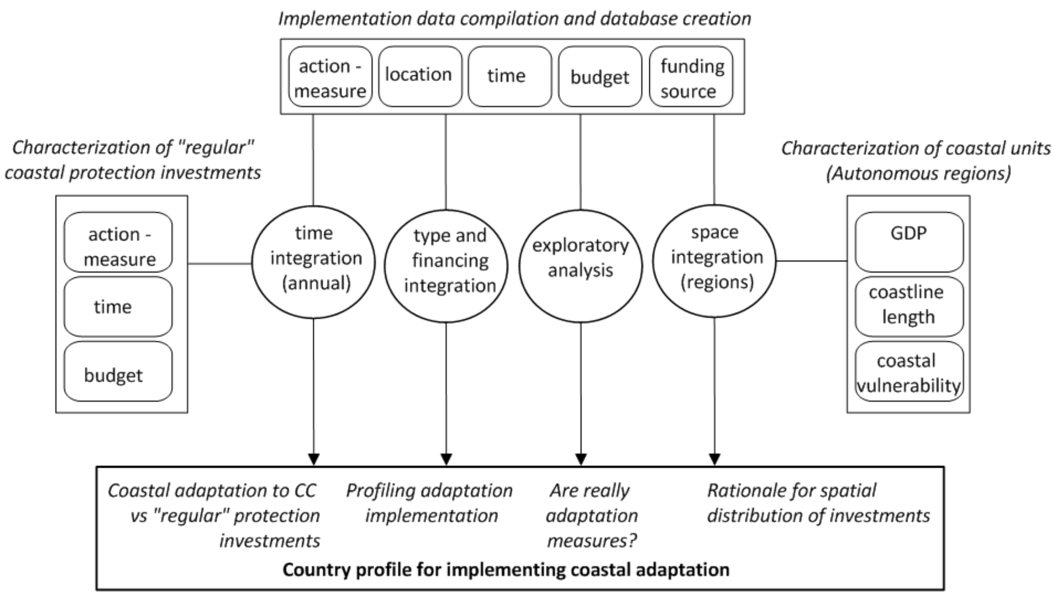


Figure 6.2. Methodological framework to analyse progress in implementing coastal adaptation measures at National scale.

6.3.2. Data compilation

The first part of the methodology consists of the compilation and analysis of investments in adaptation measures along the Spanish coast that have been explicitly (and officially) designed to address adaptation to climate change. To this end, we have built a database of measures implemented along the different coastal regions of Spain, where we compiled the types of measures, locations, budgets and funding agencies. There are two main financial sources for coastal adaptation actions in the Spanish coastal zone: the central government through the PIMA Adapta programme, established under the PNACC, and the EU, through the LIFE programme.

The PIMA Adapta programme was implemented in 2015 by the Spanish government to fund adaptation projects related to water resources, coastal areas, and biodiversity in National Parks. It is operated by MITECO through the OECC. With respect to coastal adaptation, this initiative covers a wide range of actions to restore coastal habitats and stabilise the shoreline, with the objective of reducing vulnerability to the effects of climate change. It also includes information regarding resources and uses of the territory, as well as vulnerability studies on the coast for developing regional adaptation plans. PIMA Adapta actions in coastal areas are managed by two different entities. In particular, adaptation measures implemented in the Maritime-Terrestrial Public Domain are handled by DGSCM. In contrast, the budget allocated to developing detailed vulnerability studies, as well as regional adaptation strategies, is distributed to coastal autonomous communities.

Data on investments through PIMA Adapta programme have been collected from information provided by the OECC, as well as from analysing information provided by the DGSCM on the budget distribution per fiscal year. In the latter case, only measures directly funded through the PIMA Adapta programme are accounted for. Thus, for instance, a given type of adaptation measure, such as beach nourishment, can be funded through the regular annual budget, or through PIMA Adapta. Table 6.2 shows some examples of different adaptation measures conducted by the DGSCM through the PIMA Adapta programme.

The second major source for funding adaptation measures to climate change is the LIFE programme. This is an EU programme for the environment, nature, and climate action, and has funded more than 2,600 projects since 1992. Its overall objective is to contribute to the implementation, updating, and development of environmental policy and legislation for the EU by co-financing relevant projects. This is a competitive process, and the European Commission launches periodic calls for proposals under selected "priority areas" according to a work programme. Usually, the EU co-financing rate is 50%, except in cases where projects focus on concrete conservation actions for priority species or habitats, where co-financing can increase up to 75%. The beneficiaries are public and private bodies and the objectives, tasks, and actions for different involved stakeholders, as well as financial responsibilities, are established through a grant agreement. These beneficiaries contribute to the remaining part of the budget.

Table 6.2. Examples of Environment Promotion Plan for Climate Change Adaptation (PIMA Adapta) coastal actions in different locations in Spain.

Measure	Location	Link to CC adaptation	Year	Source
Environmental recovery and beach nourishment	Castellón (Valencia)	Reduce coastal exposure Stabilize shoreline	2017	MITECO website (1)
Artificial dune creation and vegetation settlement	Malgrat de Mar (Catalonia)	Reduce coastal exposure Stabilize shoreline	2016	MITECO website (2)
Wetland restoration and environmental recovery	A Coruña (Galicia)	Maintain coastal ecosystems in good conditions Promote Nature-based solutions (NBS)	2016	MITECO website (3)
Sand management (by-pass)	Almeria (Andalusia)	Reduce coastal exposure Stabilize shoreline	2015	MITECO website (4)
Slope stabilization and coastal protection	Several municipalities in Asturias	Protect the coast	2015	MITECO website (5)
Artificial defences (groynes and breakwaters)	Almeria (Andalusia)	Reduce coastal exposure Stabilize shoreline	2015	MITECO website (6)
Groyne removal and sand re-distribution	Cartagena (Murcia)	Stabilize shoreline Mitigate erosion problems	2017	MITECO website (7)

To identify LIFE-projects that directly contribute to adaptation to climate change in Spain, the LIFE programme database was searched for projects in Spain with selected keywords (for example, coastal areas, adaptation, climate change). In this work, we only consider LIFE-funded projects from 2010 onwards, covering the period of PIMA Adapta implementation as well as some additional years during which society became more concerned regarding potential impacts of climate change. In this respect, the second work programme (WP2) of the PNACC, which is considered as a significant step for systematically addressing adaptation to climate change in Spain (OECC, 2009) was adopted in 2009. The LIFE projects classified here as investments in adaptation in the Spanish coastal zone are listed in the Table C1 in Annex C. We report on the sum of the EU contribution and co-financing from the partners.

In addition to collecting data on the funding of coastal adaptation measures, we also compiled data on the current expenditures on protection, so as to characterise the current needs to maintain, protect, and preserve the Spanish coast (referred to as regular budget). These expenditures are covered by the Spanish government through the DGSCM. Data have been collected from information provided by the DGSCM and the national general budgets on budget distribution per fiscal year and per coastal protection objective. These yearly budgets included an amount to be used for emergencies, usually associated with measures to cope with damages induced by the impact of storms. Since 2014, the DGSCM has launched yearly programs, called Plan Litoral, for funding emergency measures to repair storm-induced damages along the Spanish coast. This program is only launched in years where the frequency or intensity of storms induce very significant damage along the Spanish coast, as was the case in 2014, 2015, 2017, and 2018. Expenditures in this program have been compiled from information provided by the DGSCM characterising the current investment needs to compensate for storm-induced damages under current climate conditions.

6.3.3. Data analysis

The data analysis focuses on identifying the dominant measures and geographical rationales for investments during the first years of the implementation of the PNACC. This is completed by characterising the current context of expenditures for maintaining and preserving the Spanish coastal zone during the last decade, from 2010 to 2018.

Investments in adaptation measures were classified according to the CAS, which is consistent with the International Panel on Climate Change (IPCC) AR5 (Noble et al., 2014). It classifies actions into three major categories: (i) structural-physical, (ii) social, and (ii) institutional, and into three sub-categories based on the typology and purpose: (i) protection, (ii) accommodation and (iii) retreat. In total, the CAS considers 26 different adaptation actions, which are classified according to these two criteria (Table C2 in Annex C). Measures already implemented along the Spanish coast and funded under PIMA Adapta and LIFE projects were classified according to these criteria.

Finally, measures were grouped in more generic classes to simplify the classification (see Table C3 in Annex C), including the combination of different options (mixed type), and a class for actions where their typology was not specified (without specifying the type). The distribution of expenditures per type for each project is determined according to the provided description. When it consists of more than one measure, the investment is assigned the following budget details. In the case of projects executed in different coastal regions (this is especially applicable to LIFE projects), the budget is split accordingly, to obtain corresponding regional values.

To put investments in coastal adaptation measures into a general context, we compare them with current expenditures in coastal protection during the last decade. Current expenditures in coastal protection by the DGSCM were classified in terms of their main official objectives. To make a consistent comparison to investments in coastal adaptation, we identified expenditures associated with objectives directly covered by the CAS (see Table C4 in Annex C).

To characterise the geographical distribution of investments in coastal adaptation, the compiled data are aggregated within each coastal region. Thus, regional values of total investments and investments per type of measure were obtained for PIMA Adapta and LIFE projects.

To investigate the rationale behind the geographical distribution, we analyse the relationship between the distribution of investments and selected regional indicators characterising spatial scale, economic importance, and coastal vulnerability. These indicators are the coastline length and GDP of the coastal provinces of each region, whereas the vulnerability of each region is characterised by using an integrated value of the coastal vulnerability index (CVI), as calculated by López-Royo et al. (2016). This is a slightly modified version of the Gornitz and Kanciruk (1989) index to characterize the vulnerability of coastal areas to coastal hazards including SLR, particularly due to erosion and/or inundation. This is formulated in terms of a series of variables such as geomorphology, coastal slope, shoreline evolution, relative sea level rise, wave climate and tidal range.

6.4. Results

6.4.1. Investments in coastal adaptation

The total investment in coastal adaptation to climate change during the analysed period (2010–2018) in the Spanish coastal regions has been estimated at €56 M, from which 57% was funded by the Spanish national initiatives under the PIMA Adapta program. The remaining parts were funded through LIFE projects, which are co-funded by the EU

Commission and Spanish administration (local, regional and national). If we normalise these investments for the covered period by each source, the average current investment in coastal adaptation in Spain is approximately €8 M/year using national funds, and €2.6 M/year using LIFE project funds (considering both EU and partner contributions).

Figure 6.3 shows the distribution of such investments according to the type of measures along the Spanish coast. Approximately 40% of the total budget was dedicated to social and institutional measures. Here, the main efforts were devoted to financing research projects and studies aimed at developing regional adaptation plans and analysing adaptation options (11.8%), as well as at evaluating services provided by coastal ecosystems (14.2%). Although the analysed period covers the early stages of the funding strategy, approximately half of the total budget was used to implement structural measures (44.9%) dominated by nature-based solutions and soft measures, representing 23.1% and 14.7% of the investment, respectively.

One interesting result is that the types of measures funded differ strongly between the two funding sources. Structural measures funded through the national adaptation plan consist of soft measures (mostly beach nourishment), nature-based solutions and hard defences (21.6%, 14.4%, and 8.7%, respectively). When these type of measures are considered under the umbrella of LIFE funding, the role played by nature-based measures increases up to 34.6%, that of soft measures decreases down to 5.5%, and no hard measures are considered.

With respect to social and institutional actions, there is also a significant difference between funding sources. The LIFE funding clearly promotes this type of social and institutional actions, with approximately 60% of the investment dedicated to projects to evaluate and protect ecosystem services and to define protected areas. In contrast, 24.2% of the national funding was purely for social actions, with an absence of institutional measures. Approximately 15.5% of funds were not associated with specific types of measures, owing to a lack of relevant information.

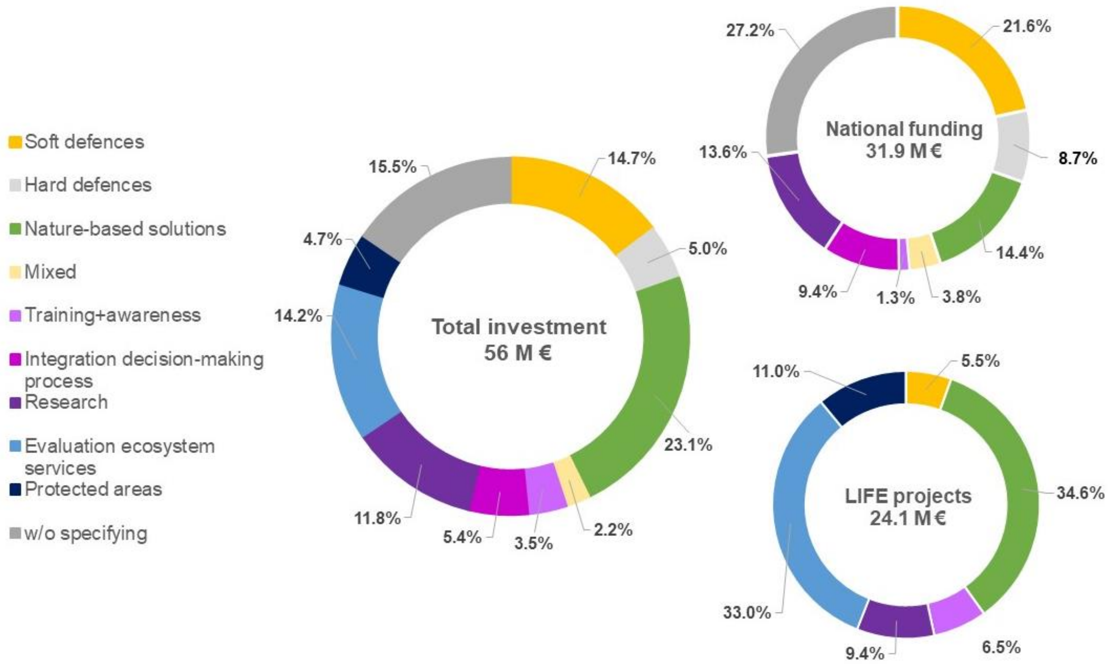


Figure 6.3. Percentage of expenditures per typology of adaptation measures in Spain.

6.4.2. Geographical distribution of investments in coastal adaptation

The geographical distribution of the investments in coastal adaptation along the Spanish coastline is shown in Figure 6.4. Most of the funding was allocated to the Mediterranean coastal zone, with the largest three regions (Andalusia, Catalonia and Valencia) concentrating approximately 73% of the regional investment distributed among the coastal regions (56% if total investment, as €12.83 M are destined for measures that are not associated to a specific region). This is partially owing to the fact that these regions have successfully attracted LIFE funds. As an example of this, approximately 70% of the total investment in Andalusia and Catalonia has been obtained through LIFE funding, with important coastal adaptation projects such as LIFE-Adaptamed and LIFE-Pletera having been implemented. These regions also concentrate the largest investment (56%) of the national PIMA Adapta program along the Spanish coastline since 2015. In contrast, Murcia, Ceuta, and Melilla present the lowest investments in coastal adaptation, with all actions being supported through national funds.

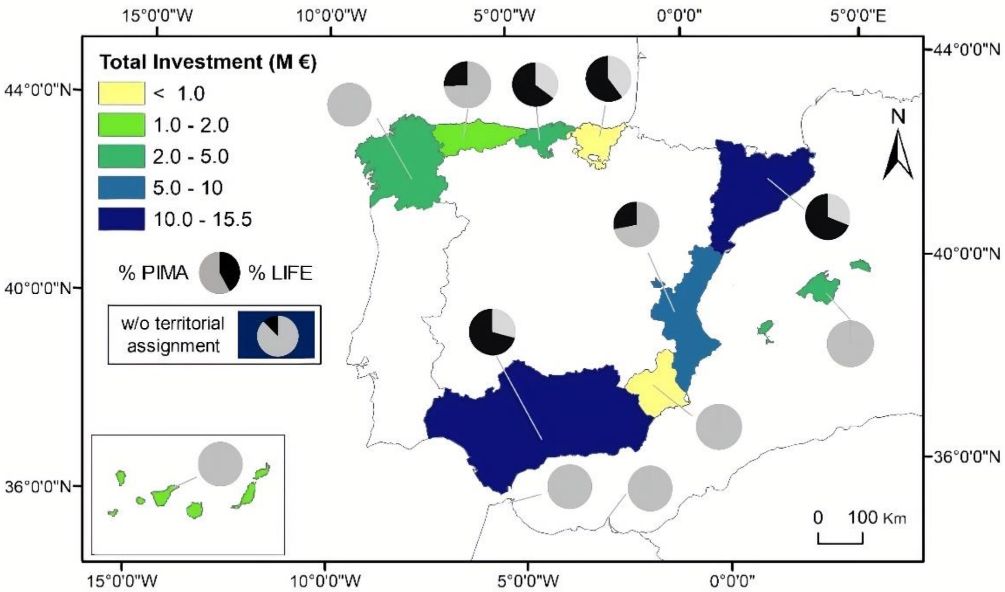


Figure 6.4. Investments in coastal adaptation to climate change in Spanish coastal regions. Note: €12.8 M are destined for general measures without specific territorial assignment.

Figure 6.5 shows the distribution of investments and selected regional indicators. When investments in a region are related to coastline length, there is an apparent direct relationship, i.e. the larger the shoreline, the larger the investment. However, when all data are considered, they are not significantly statistically correlated (Fig. 6.5a). This lack of correlation is caused by two groups of regions which depart from this general trend: (i) regions with a highly-indented coastline which results in a very large length (Galicia, Canary, and Balearic Islands), and (ii) regions comprised by an autonomous city, which results in a very short length (Ceuta and Melilla). When these regions are removed from the analysis, a very strong correlation is obtained (r^2 = 0.94) between investment and coastline length.

When investments are related to the economic importance of coastal provinces within each region, again a direct relationship is noted, i.e., the larger the regional coastal GDP, the larger the investment (Fig. 6.5b). In this case, the entire dataset follows the trend and they show a moderate correlation (r^2 = 0.57). In spite of this, Andalusia behaves as an outlier, receiving an investment much larger than expected according to its GDP. If this region is removed, the obtained correlation between investment and coastal GDP significantly improves (r^2 = 0.91).

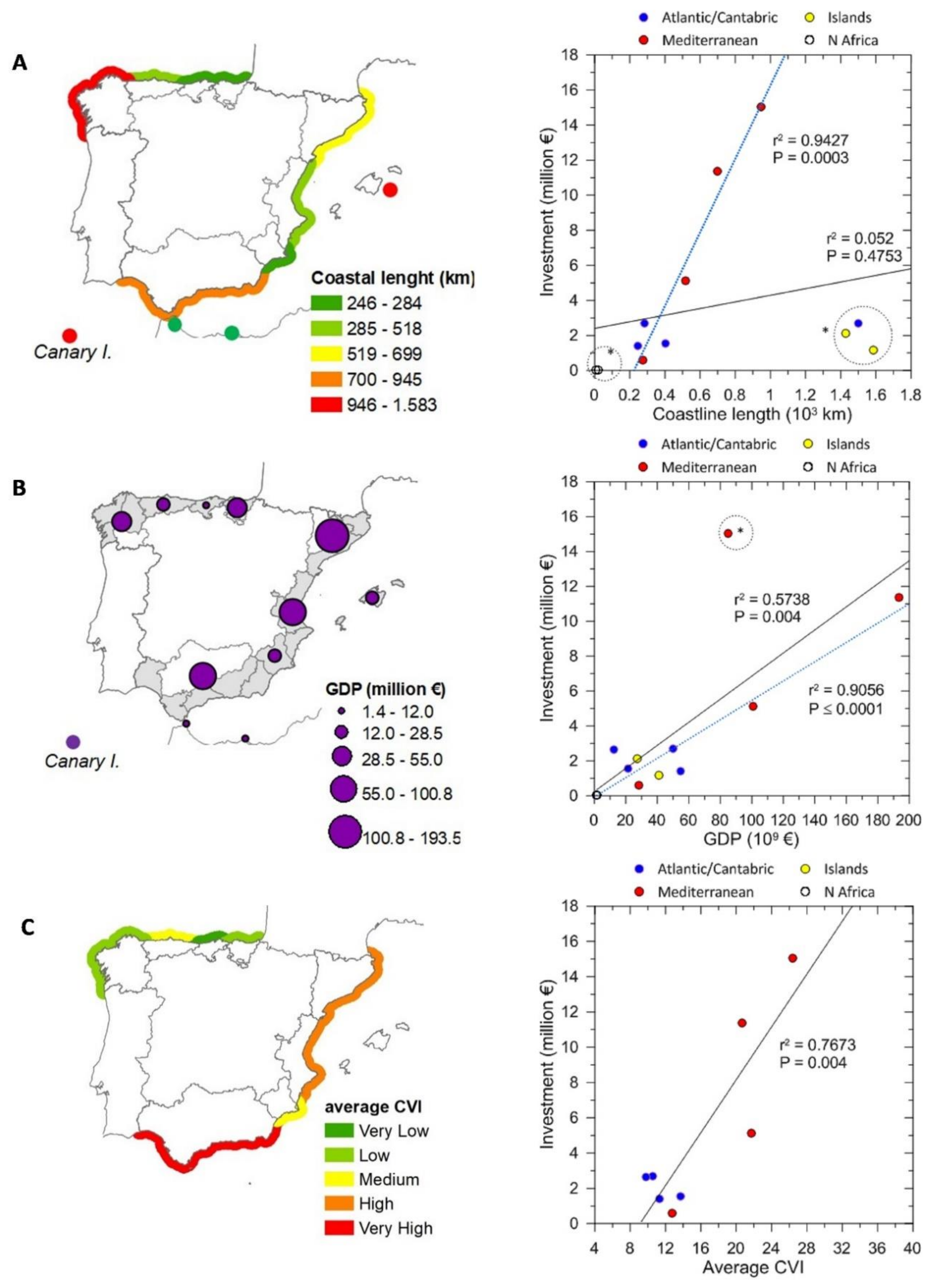


Figure 6.5. Investment in coastal adaptation per region vs. regional indicators. (A: coastline length; B: GDP of coastal provinces within the region; C: average coastal vulnerability index (CVI)). (*: indicate excluded values to obtain alternative relationship –blue dashed line-).

Finally, investments in coastal adaptation in each region were related to an overall measure of coastal vulnerability. To this end, we have used the previous results obtained by López-Royo et al. (2016) who characterised the vulnerability of the continental Spanish coastline (excluding islands and autonomous cities in North Africa) by using a modified version of the CVI. Figure 6.5c shows the investments in each region versus their average CVI values. As can be seen, regions with the largest investments (Andalusia, Catalonia, and Valencia) are classified as high or very-high vulnerability coastlines, as these areas contain the largest extensions of uninterrupted sandy beaches. Despite the fact that this vulnerability computation was not used as a decision criterion for distributing funding, the investment in each region is strongly correlated to its vulnerability degree ($r^2 = 0.77$). In other words, the larger the coastal vulnerability, the larger the investment.

6.4.3. Investments in coastal protection

To put investments in coastal adaptation measures into a general context, expenditures in coastal protection in Spain during the last decade are analysed.

Figure 6.6 shows the evolution of annual expenditures in coastal measures funded by the DGSCM since 2010. There is a significant drop in total expenditures after 2010, decreasing by about €120 million in just two years, to reach a nearly constant annual investment in regular coastal actions of €61 M/year since 2012. Here "regular" means expenditures without including storm recovery investment specific budget items (Plan Litoral). However, most of this sharp decrease (approximately 70%, €84 M in two years) was incurred under an objective of "improve and ensure the public and free use of the coast", which is not directly related to the measures covered by the CAS (see Annex C, Table C4). If we only retain the annual expenditures in measures related to adaptation options included in the CAS (see Annex C, Table C4), the current investments in coastal protection were not so severely affected (blue line in Figure 6.6).

Since 2014, the DGSCM budget has stabilized at a value approximately 55% lower than in 2010 (Figure 6.6), with an average annual expenditure of €64 M/year. From that €64 M/year, approximately €40 M/year is devoted to coastal protection projects related to options included in the CAS (Table C4, Annex C). In addition, during this period, the DGSCM has also had an average annual investment of €26 M/year in emergency measures. Considering both contributions, i.e. coastal protection measures including Plan Litoral, the average annual investment of the DGSCM under current conditions to maintain and preserve the Spanish coast is approximately €66 M/year.

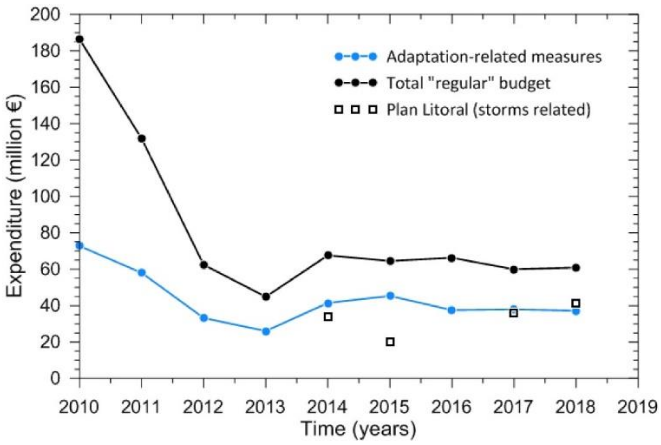


Figure 6.6. Current expenditure by the General Directorate for Sustainability of the Coast and the Sea (DGSCM) in coastal protection measures.

6.5. Discussion

In this work, we have done a first evaluation of current expenditures in adaptation measures to climate change along the Spanish coast. Until present, most of activities related to coastal adaptation in Spain were related to assessing impacts and vulnerability, capacity building actions and developing plans and strategies (e.g. European Commission, 2018). In this respect, the number of adaptation initiatives and actions to climate change placed Spain as one of the top countries in Europe and even worldwide (Lesnikowski et al., 2015, 2016). As a result of these investments, the PNACC and the CAS were approved in 2006 and 2016 respectively (Losada et al., 2019). This has opened a new period for investments, in such a way that specific adaptation measures began to be funded along the Spanish coast. In what follows, these initial investments are discussed.

Nonetheless, results presented in this study must be interpreted with caution and a number of limitations should be borne in mind. On the one hand, methodology limitations related to the lack of previous studies hamper further elaborations on previous findings. To our knowledge, this work is the first assessment on coastal adaptation investments in

Spain at this early stage of implementation. Also, the absence of an official database reflecting all investments in coastal adaptation to climate change, drives us to compile these data from different official sources of information. In this sense, when information on given implemented measures exists we are sure that they took place. But, the non-presence of such information does not necessarily imply that it does not exist. However, due to the obligations of the Administration to officially report annual investments, we assume possible deviations to be small enough. Thus, our findings can be considered reliable and valid in the sense they have been obtained from reliable sources although, formally speaking, they would represent the minimum investment made on coastal adaptation to climate change.

6.5.1. Is so-called adaptation really adaptation?

Nature-based related measures have been mostly funded under the LIFE program, whereas the PIMA Adapta program has shown a larger focus on classical coastal engineering actions (unless sediment-based measures are considered as nature-based ones). The bias of LIFE projects to this type of measure is owing to the environmental protection orientation of the program. On the contrary, although the PIMA Adapta also considers this type of measure, this early-stage funding has been mainly concentrated in classical coastal engineering measures, which are used most often to tackle current coastal problems. As coastal management in Spain is mainly oriented for supporting recreation and protection functions and most of the investments are in urban coastal zones, these approaches are often seen to be the most cost-effective measures. Gibbs (2016) also found that in terms of budget allocation, large-scale coastal protection infrastructure is typically government funded. Thus, one question left open by our analysis whether the funded projects have really been designed as an adaptation measure to climate change, or simply as short-term protection measures for solving current problems.

Funded measures based on *beach nourishment* have been generally designed to tackle current problems, providing continuity to previous works undertaken by the DGSCM where the official objectives were shoreline stabilization and coastal protection. A typical example is the nourishment of the Benifali beach (Castellón, Valencia region) in 2017, an area that has been identified as a coastal hotspot for the impact of storms (CEDEX, 2015). The budget allocated to PIMA Adapta was approximately €1 M, which is approximately 27% of all of the investments in the Valencia region within the programme. The planned and executed works were designed to recover the beach functionality under current climatic conditions, and they did not account for the potential excess of erosion owing to sea level rise. Thus, although the measure can be considered as effective in recovering the beach, it cannot formally be considered as an adaptation to climate change. In other words, even without climate change, this measure had to be enacted. This can be extended to nearly all nourishment operations funded until present under PIMA Adapta.

One of the few nature-based measures funded under PIMA Adapta is *dune building* (and vegetating). An example of this is an artificial dune in the Tordera delta coast (Barcelona, Catalonia region) in 2016. This is a coastal hotspot subject to large erosion rates and susceptible to inundation during storm impacts (Jiménez et al., 2017), and is classified as a priority area within the Maresme Strategic Plan (CEDEX, 2014). The budget funded through PIMA Adapta was €0.15 M, and it was the only physical measure funded through the programme in the Barcelona province. The dune was built during the first part of 2016 and, owing to the impact of storms on January/February 2017, it was destroyed at its northern part, where the beach was narrowest. The dune was essentially designed to prevent inundation of the hinterland during the incidence of storms and, owing to local conditions, it will hardly survive unless a minimum beach width is maintained in front of the dune. In spite of the fact that sediment eroded from the dune will contribute to the beach sediment budget, its mobilization at a very short-term scale hardly permits an assumption that it plays a quantifiable role in long-term coastal adaptation to sea level rise if no continuous maintenance is performed.

These examples of physical adaptation measures funded under PIMA Adapta have the common characteristic of being executed in areas experiencing problems under current climatic conditions, whereas the DGSCM actively invests in coastal protection. In fact, most of these actions have not been executed in an isolated manner, but they were a part of other concurrent protection works at such locations. Thus, although formally they were contributing to adapting the coast to climate change by improving its current state, the reality is that they had to be executed, even absent climate change. In other words, they were officially labelled as an adaptation measure (funded under PIMA Adapta), but they were mostly designed to solve current problems.

When these measures are considered in a long-term perspective (e.g. Hinkel et al., 2013), such as that associated with climate change adaptation, additional elements have to be considered. Thus, to enable nourishment as an effective long-term adaptation option, the existence of strategic sediment reservoirs (Marchand et al., 2011) to obtain the required present and future volumes is needed (e.g. Jiménez and Sanchez-Arcilla, 2019). Moreover, the design and execution are also key elements to be considered, i.e. continuous versus massive nourishments. An example of this is the Sand Motor project in the Netherlands, where approximately 21 M of m^3 of sand was supplied to the coast during a period of six months to counteract coastal erosion during a period of approximately 20 years (see details in Stive et al., 2013). According to the corresponding study, this would be more efficient, economical, and environmentally friendly in the long-term than traditional beach nourishments. By depositing a large amount of sand in a single operation, short-term replenishment would be unnecessary, thus avoiding repeated disruptions of the seabed, as well as decreasing unit dredging costs and taking advantage of financing opportunities (e.g. Stronkhorst et al., 2018).

This is also applicable to implementing hard measures, where functional designs under current conditions are not necessarily valid for future ones (e.g. Arns et al., 2017). A clear example of redesigning for future conditions is the Thames Barrier and its associated defences, which need to be upgraded to maintain the same level of protection. Despite being initially designed to resist flooding from storm surges, the Thames Estuary 2100 project proposed a strategy based on different adaptation pathways, depending on the rate of sea level rise (Environment Agency, 2009). Hall et al. (2019) suggest that the most cost-effective and robust adaptation pathway involves moving the Thames Barrier 17 km towards the sea if the mean sea level rises 2 m above the present level.

An example of a *nature-based solution* is the recovery of the ecological functionality of the coastal lagoon system of La Pletera (Girona, Catalonia, Mediterranean). This is an action funded through the LIFE programme (Annex C, Table C1) and aiming to restore the integrity of a coastal lagoon system that was altered by abandoned infrastructure, by deconstructing built-up areas and restoring previous wetlands and their ecological functioning. The total investment was €2.5 M, from which 75% was funded by the EU. Different local stakeholders, led and coordinated by the Torroella de Montgrí municipality, supplied the rest of the investment. The origin of the project is a former study launched and funded by the DGSCM in 2007 to recover the ecological functionality of the area. They also modified the land planning to incorporate a previously urban-delineated zone to the public domain. The project has been fully executed and, in addition to the physical measures, it included a concerted communication, education and awareness-raising strategy. Although the objective is essentially based on ecological restoration, the adopted approach, which enhances the accommodation space in the area, can be easily included in any long-term adaptation scheme to climate change.

In this context, it has to be considered that recovering coastal ecosystem functionality, together with the generation of space is the basis of the development of ecosystem-based solutions for coping with global change (e.g. Temmerman et al., 2013). Until now, the implemented measures have only been placed in uninhabited areas, which certainly avoid social conflicts. However, when using as an adaptation measure to reduce future risks, this measure would imply affecting the local population and as such, it may have social implications of different degree depending on each case (Hino et al., 2017). In this context, the Spanish experience in redefining coastal setbacks so as to free occupied space in the coastal zone to apply to the Spanish Coastal Act is quite disappointing. In most of the cases, it becomes a very long administrative process, in which the affected population uses all possible judicial resources to avoid being relocated. In practice, this implies that in addition to space, time is one of the most important resources for implementing adaptation measures based on coastal retreat (Jiménez, 2019). Thus, if this option is going to be considered, it should be recommended to start the usual long administrative process and the negotiating process with the affected population as soon as possible. This also illustrates that social and institutional measures are useful and needed, not only at the early stages, but also throughout the entire adaptation process. However, their weight in the allocation of adaptation expenditures has to decrease progressively in benefit to the other types of structural-physical initiatives.

6.5.2. What drives the spatial distribution of adaptation investments?

According to the gathered data, the regions with highest current investments in adaptation are located along the Mediterranean coast (Andalusia, Catalonia and Valencia). These regions present some common features such as relatively long coastlines, high coastal GDP, and high coastal vulnerability. They are among the most visited regions by tourists and, considering the dominant role of sun and sand tourism

(Aguiló et al., 2005), beaches are one of the main resources for economic development (Rigall-i-Torrent et al., 2011). These characteristics seem to indicate some rationality regarding investments, i.e. more vulnerable and/or economically important coastal regions can concentrate investments to progress towards better adaptations to climate change. In any case, it has to be considered that a significant part of the accounted investments are from LIFE funding (Figure 6.3), and to access them, regional stakeholders must participate in a competitive process which requires an active role. These regions caught more than 80% of the accounted LIFE funds, with Andalusia being the most successful region.

At the other end of the spectrum, two of the regions with the longest coastlines, the Spanish archipelagos of the Canary and Balearic Islands, are among the areas with the lowest current investments in adaptation. These types of insular territories are, however, also especially vulnerable to climate change (e.g. Mimura et al., 2007). Moreover, landscape transformation, associated with the dominant role of the tourism industry, has further increased the vulnerability of those islands (e.g. Pérez-Chacón et al., 2019; Roig-Munar et al., 2019). A possible explanation for such apparent underfunding could be associated to the fact that most of the existing beaches in these territories do not present significant problems of stability, and erosion is one of the major drivers in DGSCM investments in coastal protection. However, current problems related to landscape transformation and urban development are beyond the DGSCM competences, and although they can interact with climate change-induced problems, they are apparently not perceived as such. In any case, this apparent underfunding should be corrected, so as to account for territorial specificities in the near future.

One of the key elements in properly distributing investments in coastal adaptation to climate change is the existence of specific adaptation plans downscaled at the regional level, where local impacts, needs and measures are clearly defined. Once this is available for all coastal regions, solid criteria for funding distribution could be established. Without this, current investments are usually distributed using criteria based on current protection needs and, some generic elements, such as coastline length. In some way, this replicates the results obtained by Policy Research Corporation (2009a) when analysing coastal protection expenditures in the EU, which found that a small group of countries concentrated most of the investments (Spain was one of them). Countries more advanced in coastal protection and climate adaptation are in general those that are most affected by coastal hazards, and that have experienced severe weather events in the past. This can be observed specially in the North Sea countries concerned with flood risk, with the UK and the Netherlands as forerunners. The main difference is that, at European level, each country decides how much is invested in adaptation, whereas, at the national level, the government decides how the overall budget should be distributed. As previously mentioned, the active involvement of coastal regions in LIFE projects can attract additional and significant investments and, for the short period analysed, they have played a relevant role in determining the final expenditures in adaptation.

Considering that the current beach management in Spain is oriented towards recreational uses owing to their importance to the local economy, mobilising private finance would pump resources into coastal adaptation and protection investments. Future efforts on coastal adaptation should focus on grant financing and aligning public stakeholder and private investor interests in coastal adaptation projects, to overcome prevailing barriers and to help close the coastal adaptation-financing gap (Bisaro and Hinkel, 2018). In fact, coastal adaptation is often attractive from a purely economic perspective for soft and hard measures to maintain benefits from tourism (Hinkel et al., 2013), and require efficient coastal adaptation measures to maintain future beach widths to properly support tourist demand (e.g. López-Dóriga et al., 2019). However, they could also generate indirect revenues, as the associated tourism activities could be taxed (Kok et al., 2017). Therefore, delineating tax rates to account for unequal benefits of public funds could facilitate local investments in coastal adaptation (Mullin et al., 2019). Consequently, promoting public-private partnership with powerful (economic) stakeholders, for example, the tourism industry, can enhance coastal adaptation, as insufficient investments during earlier stages in changing conditions may lead to an increase in future expenditures.

6.5.3. Coastal adaptation to climate change *vs.* regular protection investments

Expenditures in coastal protection in Spain at the beginning of 2000s (2000–2008) were among the five highest in Europe, with an average annual expenditure of approximately €52 M/year (Policy Research Corporation, 2009b), with values even higher during the 1990s, up to €82 M/year (Barragán, 2004). However, the national coastal budget significantly decreased after 2009, coinciding with the peak of the recent economic crisis (Fig. 6.6). Therefore, the analysed period can be characterised by a relatively low investment in regular protection and adaptation to climate change measures as, even adding both together, the annual investment would not reach the values before the economic crisis.

During the last decade, and specifically from 2014 to 2018, the Spanish coastline has experienced significant damage associated with the impact of storms, in such a way that specific recovery programmes (Plan Litoral) were required (Fig. 6.6). The spatial distribution of these investments depended on where storm occurred, and hence was concentrated in neighbouring regions during a given year (Fig. 6.7). As an example, the 2014 programme was fully dedicated to the Cantabric/Atlantic coastal regions, to compensate for damages induced by the storm season of 2013/2014, which also significantly damaged the coast of southeast England and France (e.g. Masselink et al., 2016). In contrast, the 2017 programme was dedicated to the Mediterranean coastal regions.

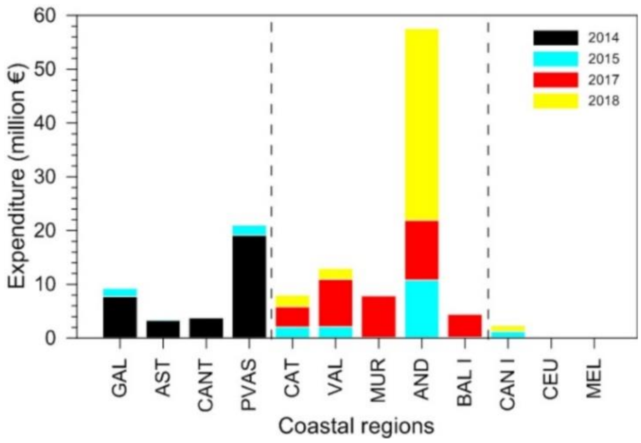


Figure 6.7. Regional distribution of storm recovery programmes (Plan Litoral). (Location of regions can be seen in Figure 6.1).

These damages, and consequently the budgets required for recovery, are expected to increase with time. Jiménez et al. (2012) detected an increase in coastal damage along the Catalan coastline in recent decades. They found that this increase was not related to any trend in storminess, but rather was associated with a progressive decrease in the protection capacity of eroding beaches. Thus, any scenario of sea level rise and subsequent induced shoreline retreat will even further decrease the protection provided by beaches to storm impacts (e.g. Jiménez et al., 2017). All of these characterises the Spanish coastline as vulnerable to storm impacts, with expected increasing budget demands for recovery measures owing to the effects of sea level rise. Thus, the lack of adequate investment for maintaining beaches at optimum configurations to provide protection against the impacts of storms will tend to increase the needs and importance of this additional budget. In other words, if less money is currently invested, future expenditures will significantly increase above expected levels.

On the whole, coastal protection and climate change adaptation activities are highly interlinked. In Spain, it is difficult to indicate which part of the investment is solely made in relation to climate change adaptation. Thus, adaptation measures are undertaken together with regular coastal protection activities. In fact, some management policies and procedures for coastal natural hazards are often seen as able to be managed without having an activated coastal adaptation plan in place (Gibbs, 2016). However, there is no existing framework designed to systematically assess the adaptation progress at the national level (UNEP, 2017). Tracking how adaptation is taking place allows researchers to document best practices, to facilitate early adoption of efficient adaptation measures, and to assess progress of adaptation efforts over time and space (Berrang-Ford et al., 2019). In spite of being costly, investing now in coastal adaptation will bring greater benefits in the future, and a monitoring plan of adaptation will enable us to learn lessons regarding what works, where and why.

6.6. Conclusions

Understanding the costs of adaptation, how adaptation has been and is currently being funded, and what funding mechanisms have been used, and following the criteria to distribute the investments will help in decision-making for the long-term planning and implementation of adaptation measures. Within this context, this work analysed how coastal adaptation is being financed in the early stages of implementation of the CAS in Spain.

According to the strategy, financing options will be specified once measures have been defined and prioritised. At the current stage, and in the absence of a detailed implementation plan, coastal adaptation has been financed through national (PIMA Adapta) and EU funds (LIFE projects). Measures financed through PIMA Adapta are mainly based on traditional coastal engineering actions, and they are implemented in areas experiencing problems under current climatic conditions. Thus, although they would contribute to adaptation by improving the current state of the coast, they would need to be implemented even under a non-changing climate. This makes the identification of the part of the investment that is solely related to climate change adaptation a difficult task. Consequently, it may affect tracking the adoption and implementation of adaptation in reality. Adaptation measures using LIFE-funding are more oriented towards nature/ecosystem-related actions, owing to the conditions imposed by this funding programme. In most of the cases, although they were designed as environmental/ecological restoration actions, they also play out as adaptation measures.

Solving current coastal problems under the guise of adaptation is a two-sided concept. On the positive side, it allows to improve the current coastal status, which will enhance adaptation to future changes. However, unless additional climate-induced effects are accounted for the design of measures, these investments will be insufficient for coping with future changes. A simple way to assess whether future conditions are considered in the design of coastal measures is by analysing the time evolution of investments in coastal protection. In Spain, with large vulnerable areas under current conditions, anything that it is not an increase in total expenditure with respect to previous years would indicate an underinvestment in coastal adaptation.

All coastal adaptation actions analysed here have been financed through public funds. This is a legacy of the traditional coastal protection policy, which allocates to the State the competence, the right, and the obligation to protect our coasts. However, coastal adaptation can be tackled through different alternatives, with various consequences for the stakeholders. This can be an opportunity to access private financing for adaptation by selecting alternatives that, while meeting official sustainability targets, also permit meeting the specific needs of stakeholders. In countries with an important coastal tourism industry and/or a large part of the GDP associated with the tourism sector (for example, many Mediterranean countries), contributing to financing coastal adaptation could be considered as an additional cost in this sector.

Although the adaptation resource considered here is money, time is the most evident declining resource. Although we are at the beginning of the implementation of adaptation measures, these need to be undertaken and implemented with respect to time. Delays and/or actions not taken properly and timely during the initial stages could result in higher costs arising in the future. Finally, it has to be stressed that the misuse of the concept of adaptation measure will tend to the society to be overconfident about adopted actions whereas they are not really progressing to real adaptation. To overcome this risk, it is necessary to have a clear roadmap for implementing adaptation measures together a proper financing structure.

Chapter 7

Adaptation strategies for the Catalan coast

7.1. Introduction

This Chapter presents different adaptation strategies to cope with the impacts of SLR on the Catalan coast focused on the management of the two analysed functions: (i) maintenance of recreational uses, and (ii) conservation of areas of high natural values.

There is an urgent need to plan our response to climate change, where in addition to mitigation policies; adaptation will play an essential role. Since any decision on adaptation over time implies a deep uncertainty (Hallegate et al., 2012), the design of dynamic adaptive plans have emerged as a key option (Haasnoot et al., 2013, 2019; Hallegate, 2009; Hallegate et al., 2012). In this context, an *adaptation pathway* is a decision-making strategy that involves a sequence of manageable steps in terms of alternative ways to achieve objectives over time. Central to this approach is the concept of *adaptation tipping point* (ATP), condition under which a particular action no longer achieve the specified objectives and a new action is necessary (Kwadijk et al., 2010). As a result, the adaptation pathway approach presents a series of consecutive and planned measures after a tipping point in the shape of a decision tree. Each decision within an adaptation pathway is triggered when changing conditions cross a threshold beyond which an unacceptable level of risk to the function is likely to arise. The timing of the ATP for a given action strongly depends on the considered scenario. Thus, the faster the rate of change is, the earlier the decision on adaptation will be. Moreover, they must consider both the timing to make the decision on measure to be implemented and the timing to implement such measure (Haasnoot et al., 2019).

Here, the practical goal is to present and compare different adaptation strategies oriented to a specific function in order enable coastal managers to develop suitable and sustainable adaptation plans and create a strategic vision of the future.

7.2. General criteria

The selection of alternatives and related actions demands a prioritisation by introducing specific criteria to manage analysed coastal functions. Although this is a policy option, in this work such priorities have been defined in agreement with the Coastal Adaptation Strategy (CAS) and the National Planning Framework for Adaptation to Climate Change (PNACC). Thus, the two basic criteria are:

- Where beaches are used for recreation and tourism, the functionality of the coast should be preserved. This implies to maintain the beach width within optimum values to provide the required recreational carrying capacity.

- High natural value areas located on sensitive stretches to SLR (i.e., low-lying coasts) should be managed to enhance its natural resilience, giving priority to nature-based solutions wherever possible.

7.3. Adaptation strategy for the recreational use of the coast

7.3.1. Acceptable limit for the current strategy

Prior to defining any adaptation strategy, it is necessary to set an acceptable level of potential risk referring to the state and functionality of the socio-economic system (Losada et al., 2019). Responsible stakeholders will select this level of acceptability, and it will determine when actions need to be implemented. In this work, we have assumed a given (arbitrary) risk threshold, although this can be modified by the competent Administration.

When dealing with economy, the selection of a risk threshold is a tricky task since, in general, any variation in the GDP would cause a great concern. In this context, we have selected a 2% decrease on the total GDP as the threshold to take adaptation actions.

According to the analysis done in Chapter 3, this value can be translated approximately into a 20% decrease in the contribution from tourist activities which corresponds to a 20% reduction in the PCC (physical carrying capacity). Such change in the economy would represent a loss of more than €2,500 M in 2019 values and more than 36,500 work positions in Catalonia. It is important to highlight that the definition of this threshold is considered apart from any external factor, such as the case of COVID-19 pandemic whose recorded decline for Spain GDP was 18.5% for the second quarter 2020 (Eurostat, 2020).

Figure 7.1 shows the projected reduction in the PCC for the entire Catalan coast under given SLR scenarios. As it can be seen, the threshold of tolerable risk will be reached by 2035 under both RCP scenarios, while it will occur 5 years sooner under H+. Table C5 in Annex C shows the differences for the expected timing for this initial ATP considering different management targets based on different assumable PCC losses.

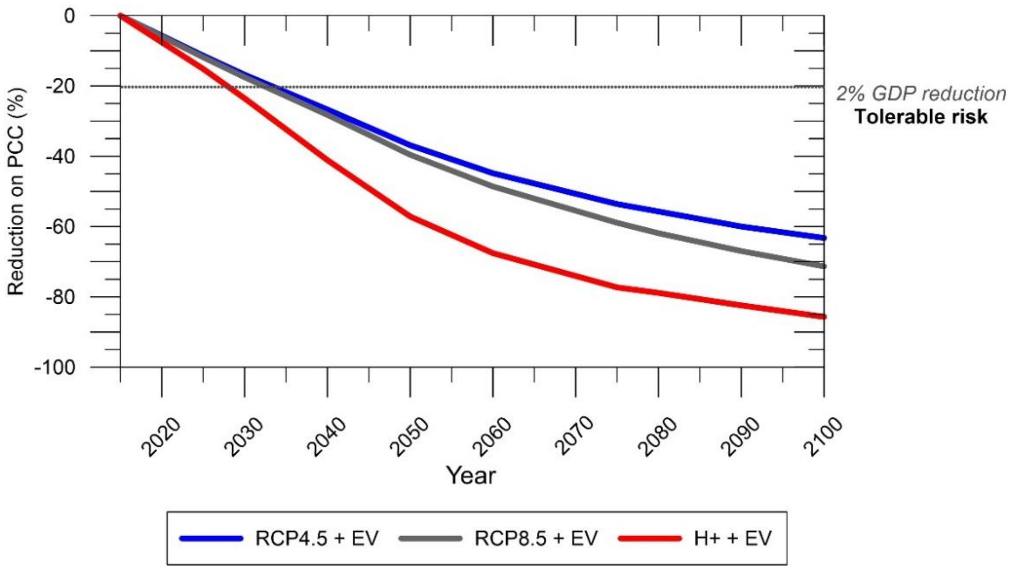


Figure 7.1. Projected reduction in PCC (in %) for the entire Catalan coast at different SLR-scenarios. In this work, 20% decrease in PCC is considered as the tolerable threshold for starting adaptation associated to a reduction of 2% of GDP.

This timing for adaptation is not uniform along Catalonia since there is a high spatial variability in beach PCC, magnitude of the impact and contribution to GDP among coastal comarcas. Thus, it is expected that Costa Dorada will be the first tourism brand requiring adaptation, which must start to be implemented in about 10 years (2030) under RCP scenarios, whereas this tolerable threshold will be reached in about 15 years (2035) for

Barcelona and Costa Barcelona, and in about 20 years (2040) for Costa Brava (Table C5 in Annex C).

Adaptation measures to propose a strategy to manage coastal recreation under the influence of SLR have been selected taking into account alternatives considered within the PNACC and the CAS (López-Dóriga et al., 2020): (i) beach nourishment, and (ii) spatial tourism planning. The former corresponds to the most widely applied structural/engineering measure, whereas the latter refers to a coastal planning strategy to redistribute users in areas with enough carrying capacity. These strategies are presented in what follows.

7.3.2. Beach nourishment

7.3.2.1. Specific criteria

In general terms, beach nourishment can be defined as the artificial addition of suitable quality sediment to a beach area that has a sediment deficit to maintain its width for a specific purpose, such as protection or recreation (Dean, 2003). As it was introduced in Chapter 2, this optimum beach configuration for recreational purposes in the Catalan coast corresponds to a width of 40 m. To implement this adaptation measure the following conditions have been imposed:

- Nourishment is only applied in urban and semiurban beaches to compensate SLR-induced effects when the maximum saturation level (4 m^2/user) is exceeded.
- Since the management target is recreational, and no changes in beach typology is considered, natural beaches are not nourished in spite of being eroded. As a consequence, Ebro Delta beaches (Baix Ebre and Montsià coastal comarcas), among others, are not nourished under a recreational planning perspective. This does not imply that natural beaches could be nourished under other criteria defined by the competent Administration.

These criteria have been selected to optimize the use of the available sand stock. A generalized beach nourishment strategy would imply, in addition to higher costs, an earlier depletion of the resource and, consequently, an early reaching of the tipping points.

7.3.2.2. Methodology

The methodology to define this adaptation measure comprises the following steps:

1. *Calculation of required volume to nourish beaches*

The first task is to evaluate the volume required to compensate losses associated to shoreline changes (ΔX). The volume of sediment required per unit length of shoreline (ΔV) is here simply estimated by assuming that shoreline changes result in a parallel displacement of the active beach profile, which is defined from the berm (B) down to the closure depth (d_c) (Eq. 7.1),

$$\Delta V = \Delta X(B + d_c) \tag{7.1}$$

The success of a nourishment scheme strongly depends on the compatibility of the borrow sediment with respect to the native sand (Dean, 2003). Since beaches along the Catalan coast are of varying sediment sizes (CIIRC, 2010), they will require borrow sediment of different characteristics. The proper selection of such material will control the expected sediment losses which are usually represented through the overfill factor. To simplify the analysis, in this work, full availability of suitable borrow material is assumed, and a general overfill factor of 1.05 is applied to compute nourishment volumes with respect to required ones.

2. *Aggregation to a given territorial or management unit*

Required nourishment volumes are calculated for each beach, and then they are aggregated up to a given management unit. Available sediment stocks are public goods to be administrated by the Government of Spain, and they could be obtained and used across different autonomous communities. In spite of this, in this work we assume that the maximum management unit is given by the Catalan coast, and that the competent Administration will set up the criteria to distribute the material within such unit to meet local demands.

In order to mimic the role of the competent Administration, and because the target is to manage recreational beaches, we have defined the tourism coastal brand as the integration management unit. Moreover, in order to distribute the existing available sand stock among different units to meet nourishment needs, two criteria are considered: (i) physical, as a function of the sandy coastline length of each unit; and (ii) economic, based on the number of tourist accommodations within the unit, which is a proxy of the potential demand of beach resources, and highly related with the recreational component of the GDP (López-Dóriga et al., 2019). This approach serves to frame adaptation strategies according to social and territorial constraints and capacities (see e.g. Adger et al., 2009; Dupuis and Biesbroek, 2013; Ford et al., 2010).

3. *Definition of available stock of sediment*

The main ATP controlling this adaptation measure will be controlled by the existence of enough sediment resources to implement it under a given SLR scenario. In this context, the concept of strategic sediment reservoir introduced after the Eurosion project (Marchand et al., 2011) plays an essential role. This is especially evident when beach nourishment needs to be periodically done, which is the case in adapting to SLR-induced erosion. Although this stock should be established by evaluating existing sediment resources in the shelf susceptible to be exploited, in this work has arbitrarily been fixed just to illustrate the development of the strategy. To this end, two different potential sediment stocks have been selected, which are given by: (i) a volume equivalent to the cumulative nourishments done along the Catalan coast during the last decades (1980-2010); and (ii) a multiple of this amount (here taken as two times).

4. *Identification of the sell-by date*

Finally, the timing of this action is identified when the established ATP for this measure occurs. This sell-by date depends on the considered SLR-scenario and defined objectives. Two conditions have been defined: (i) whenever the current PCC cannot be maintained (i.e., no variations in the current economy); and (ii) when the assumed threshold of 2 % of the GDP is reached.

7.3.2.3. Results

1. Sand volume requirements

The estimated cumulative volumes of sediment required for beach nourishment to compensate losses resulting in widths narrower than 40 m are 101.8 M m^3 and 123.9 M m^3 by 2100 under RCP4.5 and RCP8.5 scenarios, respectively (Fig. 7.3a and Table C6 in Annex C). This amount nearly doubles up to 255.1 M m^3 under the H+ scenario.

It has to be stressed that these amounts result of a strategy based on maintaining PCC in urban and semiurban beaches, and any change on this would imply a drastic change in the required sediment stock. As an example, under RCP8.5, the required volume by 2100 would rise up to 152.2 M m^3 and 300.0 M m^3 to compensate induced erosion (without the 40 m width condition) in (i) recreational beaches, and (ii) all beaches, including natural ones, respectively. Required sediment volumes under different nourishment criteria and SLR scenarios are shown in Annex C, Table C6.

The disaggregation of these cumulative sand requirements by 2100 under RCP8.5 at the tourism brand scale is indicated in Fig. 7.2. As it can be seen, Costa Barcelona will be the most demanding brand requiring 45.3 M m^3, which represents 36.6% of the total. Costa Brava and Costa Barcelona will require similar amounts of material, roughly 30% of the total each one, whereas the needs for Barcelona will only represent the 3.7% of the total (Fig. 7.2 and Fig. 7.4). Estimated sediment needs for each tourism brand under different scenarios can be seen in Annex C, Table C7.

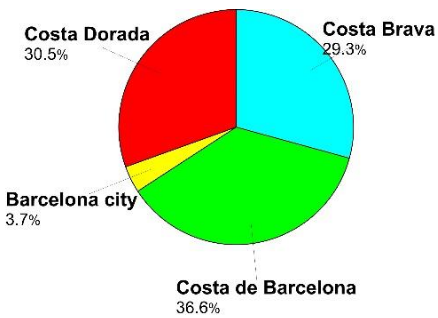


Figure 7.2. Distribution of sand among tourism brands under RCP8.5 scenario by 2100 considering the nourishment criteria defined in this work (total required: 123.9 M m^3).

These volumes would theoretically permit to sustain the economy related to beach recreation, in that contribution linked to PCC since this would be preserved. Under an adaptation strategy of assuming a 2 % decline in GDP, the required volumes would reduce and measures should be implemented later. Thus, for the most restrictive criteria under which only recreational beaches are nourished to compensate up to 40 m width, the total required sediment volumes by 2100 will decrease down to 81.8 M m^3, 103.9 M m^3 and 204.1 M m^3 under RCP4.5, RCP8.5 and H+ scenarios, respectively (Fig. 7.3b).

2. Timing of the action

Figure 7.3 shows the limits of this action as a function of sediment availability, which were set in 25 M m^3 and 50 M m^3. For the strategy of adapting to maintain current PCC, beach nourishment would be feasible by itself until 2040 and 2060 under RCP8.5 for both stocks respectively. In the case of the 2 % GDP decrease strategy, the feasibility of nourishment will extend about 15 years. Temporal variations in the timing of this action under different SLR scenarios and management strategies are shown in Annex C, Table C8.

The existence of a limited sediment availability implies to decide on how to distribute among the different tourism brands to meet their needs to locally adapt to SLR. Although this is policy option, here we mimicked this decision by using physical and economic features (Table 7.1). If the distribution is based on the extension of beaches within the unit (physical criterion), Costa Barcelona and Costa Dorada will receive the largest amount of sand, whereas Costa Brava will be the most benefited using the economic criterion due to the highest contribution of their beaches to the GDP.

Table 7.1. Distribution criteria of the available sand for beach nourishment by tourism brands.

Tourism brand	Physical criterion	Economic criterion
Costa Brava	29%	41%
Costa de Barcelona	35%	16%
Barcelona city	5%	17%
Costa Dorada	31%	26%

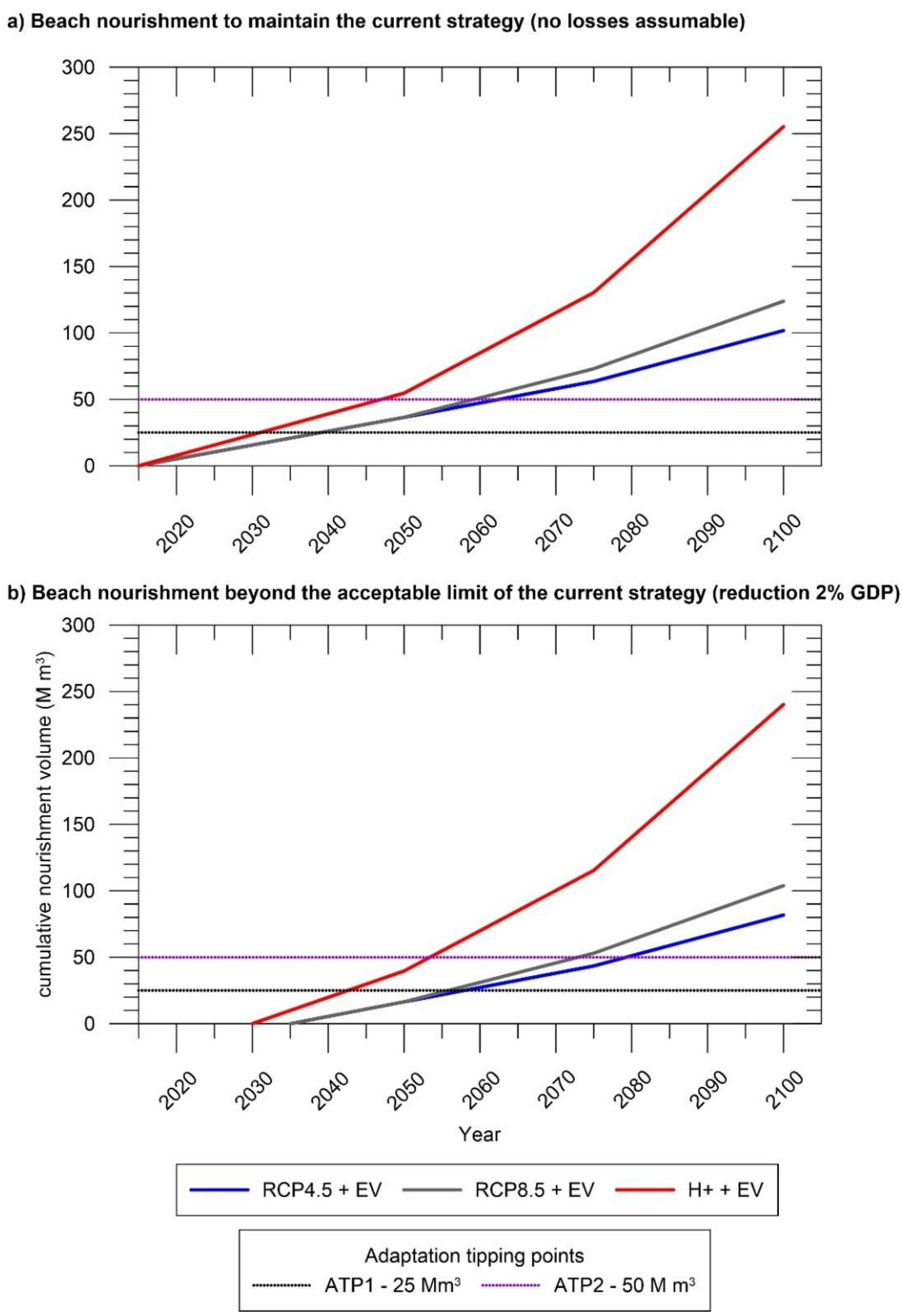


Figure 7.3. Sand volume requirements for nourishment and ATPs assuming (a) no economic losses; or (b) after a 2% decline in GDP.

As a consequence of this sediment stock distribution, the timing of nourishment will vary among tourism brands (Annex C, Table C9). Considering a total sediment stock of 50 M m^3 and for the strategy of maintaining current PCC, the feasibility of nourishment to adapt to SLR would be similar for all tourism brands if this stock is distributed using the physical criterion (Fig. 7.4, discontinuous green line). Thus, under the RCP8.5 scenario, nourishment will be a valid adaptation measure by itself until 2060 for Costa Brava, Barcelona and Costa Dorada, and until 2055 for Costa Barcelona. However, if the distribution is done based on economic criterion (Fig. 7.4, discontinuous pink line), significant timing differences would appear along the coast. Thus, under RCP8.5, the "allocated" volume of sediment for Costa de Barcelona would satisfy their local needs until 2035, whereas those for Costa Brava will be able to implement this action during the second half of this century (Annex C, Table C9).

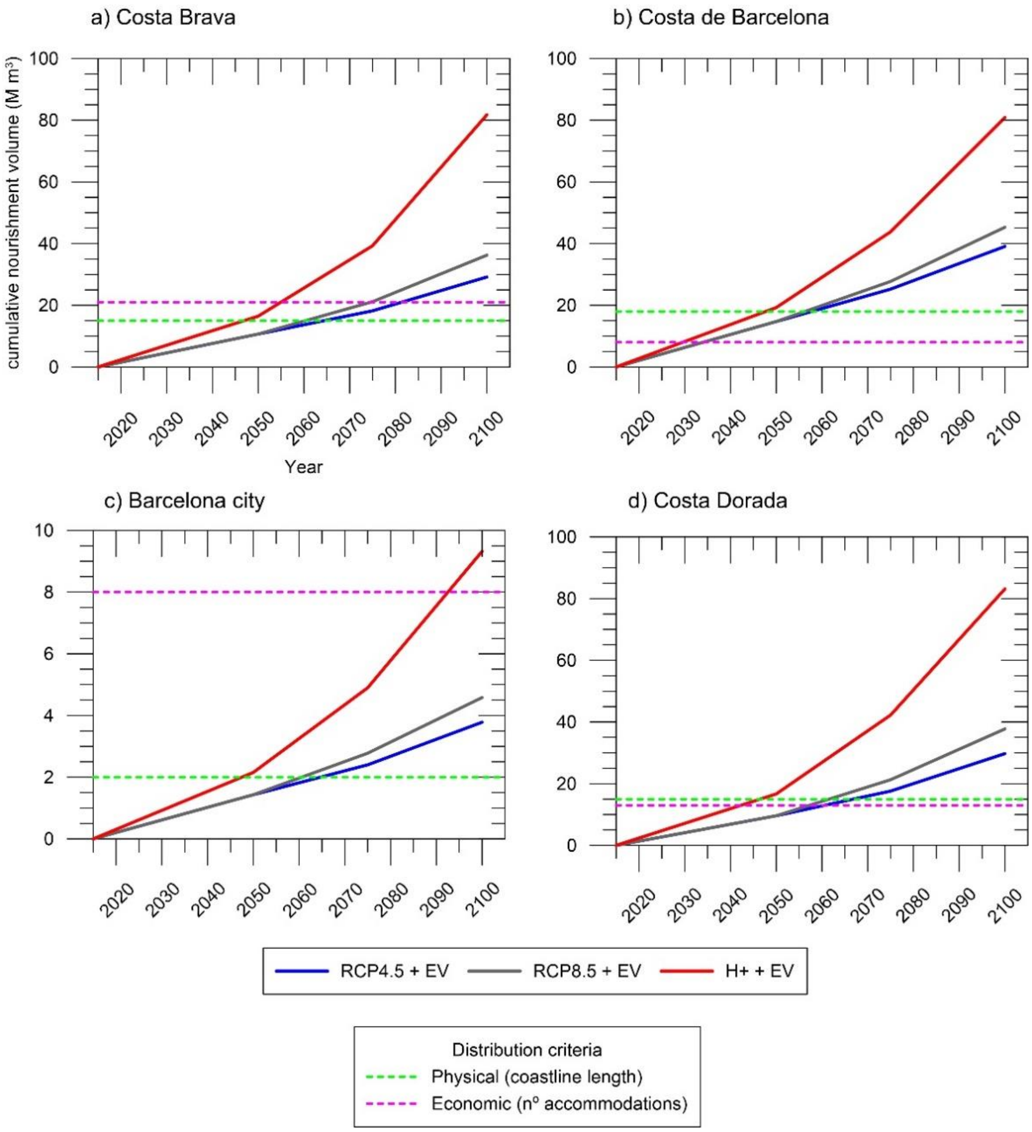


Figure 7.4. Sand volume requirements among tourism brands for nourishment and ATPs based on the distribution criteria defined by the competent Administration considering a total sediment stock of 50 M m^3. Note: sand requirements for Barcelona brand are approximately 10 times less than the other tourism brands.

7.3.2.4. Discussion

Given than the adaptation process interacts between natural and social systems, it is important to integrate perspectives from technological limits, economic and financial barriers and social conflicts into adaptation planning (Hinkel et al., 2018).

Technological limits. From a technological point-of-view, the availability of adequate volume of sand is a challenging task. On the one hand, the borrow sand must be compatible to the native sediment of each beach, in terms of size, texture, composition and colour. On the other, sand requirements increase as sea level rises leading to a rapid depletion of sand reservoirs. Therefore, some uncertainties appear associated to the availability of good quality material and the rate at which it is needed. In fact, Hanson (2002) suggested that the great challenge for this measure will be to find suitable borrow areas in the near future. Specifically for the Catalan coast, current estimates of traditionally used shallow sediment stocks are insufficient to cover expected needs (Galofré et al., 2018), so, the great challenge is to find a strategic sediment reservoir (Marchand et al., 2011).

Economic barriers. Generally, this action is beneficial in areas of tourism development since coastal tourism contributes substantially to the economy. Current standard costs per cubic meter of sand range between €6-10, for relative short-distance borrow to nourishment sites. By applying these values to the required volumes of sand, in cost-benefit terms, adaptation is profitable for these areas since associated costs are much lower than expected losses if actions will not be taken to prevent the reduction in the carrying capacity of beaches. However, unit costs are expected to increase since nearshore sites from which sand is currently derived are expected to be exhausted, and deeper and at longer distance deposits should be required. Moreover, prices are likely to rise due to lack of contractors available to undertake nourishment works coupled with the increase in its demand, already observed in the Netherlands (Hillen et al., 2010).

Table 7.2. Comparison between nourishment costs and projected losses in tourism GDP.

Year	Cost of nourished sand (M €)			Reduction in tourism GDP (M €)		
	RCP4.5	RCP8.5	H+	RCP4.5	RCP8.5	H+
2050	219 - 364	219 - 364	328 - 546	4,833	5,222	7,681
2075	381 - 635	438 - 730	782 - 1,303	7,361	8,175	10,894
2100	611 - 1,1018	743 - 1,239	1,531 - 2,551	8,762	9,952	11,955

Finance barriers. At present, the costs of beach nourishment are financed by the Central Government. However, it is not clear how long public finance can maintain these actions in the near future. Future nourishment projects could be financed by Public-Private Partnerships given the multiple beneficiaries from maintaining beaches to support the recreational demand. In fact, there is a strong relationship between price hotels and the distance to the beach (Alegre et al., 2013). Particularly for Catalonia, Rigall-i-Torrent et al. (2011) analysed the effects of beach characteristics (e.g., length, width, sand type and beach services) and location on hotel prices showing 13-17% increase, on average, for those in front of a beach. Therefore, powerful economic stakeholders with high stakes in beaches, such as the tourism industry, could contribute for beach nourishment in terms of tax revenues.

Social conflicts. Beach nourishment can diverge private interests, such as tourism, favouring this action and environmental activist opposing it. Despite being a “soft” action often considered as environmental-friendly, this measure can cause damage to the adjacent *Posidonia oceanica* meadows (González-Correa et al., 2008). Apart from conflicting interests (economic *versus* environment), different administration levels managing the Spanish coastal zone show a lack of coordination between them leading to a des-integrated management without a defined medium-long term strategy for beaches (Ariza et al., 2008; Jiménez et al., 2011). The citizen platform *Preservem el litoral* opposed to nearshore dredging claiming that this action promote unsustainable coastal management and demanding a new integrated coastal management model with more public participation.

7.3.3. Spatial planning

7.3.3.1. Specific criteria

This measure consists of allowing the distribution of potential beachgoers along the territory to sustain the future carrying capacity without implementing structural actions to avoid losses on beach surface. In this case, adaptation will be accompanied by spatial planning policies by developing new infrastructures and services in areas with enough space on beaches to accommodate the potential users' demand. The implementation of this measure assumes the following:

- Areas with enough carrying capacity on their beaches will absorb the excess of demand from others with insufficient PCC.
- In consistency with the general restriction for natural beaches, the Ebro Delta with more than 50 km of beaches is not taken into account since it would imply a major transformation of the area losing its natural characteristics.

7.3.3.2. Methodology

1. Identification of sender/receiver areas

The first step involves the evaluation of how beachgoers can be distributed along the territory. To do this, potential "sender" and "receiver" areas are identified. The former correspond to those whose PCC will be lower than their corresponding demand whereas the later have a larger PCC than the needed to sustain its local demand. Following the acceptability limit of the strategy, the distribution of users is triggered when the carrying capacity is affected by 20%.

When a beach is mainly used or exploited for recreational purposes, two types of use can be distinguished: (i) tourist, and (ii) leisure. The former represents coastal tourism as one of the most important economic activities whereas the latter represents the social service provided by beaches. Although the analysis done in Chapter 2 focuses on the tourist component (tourist BCC), the social component must be also considered when designing adaptation. In this section, an equally distributed use of beaches between both components is assumed, i.e., 50% of the PCC for local residents and 50% for tourists.

Furthermore, to ensure the maximum potential tourist demand on beaches, 100% of potential tourists (given by the number of accommodation places) is assumed that will go to the beach.

2. Aggregation to a given territorial unit

Once the PCC is estimated for each beach, values are integrated within a given management unit to assess the distribution capacity of users within such unit in terms of "absorbing" the maximum potential demand. Given that there is no a fixed criterion about users' distribution, and following the analysis done for beach nourishment, values are scaled up to the entire territory of Catalonia simulating the maximum users' mobility.

3. Identification of the sell-by-date

As the previous measure, the timing of this action is established based on when triggering this action: (i) from today to avoid any variation in the economy or; (ii) when the tolerable risk for the economy is reached. In this case, this situation is achieved when the capacity is less than 80% since the tolerable risk threshold for the economy (2% decline in GDP) is exceeded from this value.

7.3.3.3. Results

1. Sender/receiver areas

Fig. 7.5 shows the long-term projection (by the year 2100) of the sender (in red) and receiver (in green) areas of beach users under the different SLR-scenarios, with redistribution starting when the economic risk threshold is exceeded. For the RCP8.5 by 2100, there will be 37 sender municipalities unable to sustain the potential beachgoers', being the Costa Brava the largest sender tourism brand. On the other hand, 23 municipalities will be capable of absorbing the excess of demand, most of them located in the Costa de Barcelona tourism brand. As expected, the number of municipalities able to absorb users will decrease as sea-level rise, concentrating the users' distribution in 11 municipalities for the most-extreme scenario (H+), being Costa Brava and Costa Dorada the most affected tourism brands.

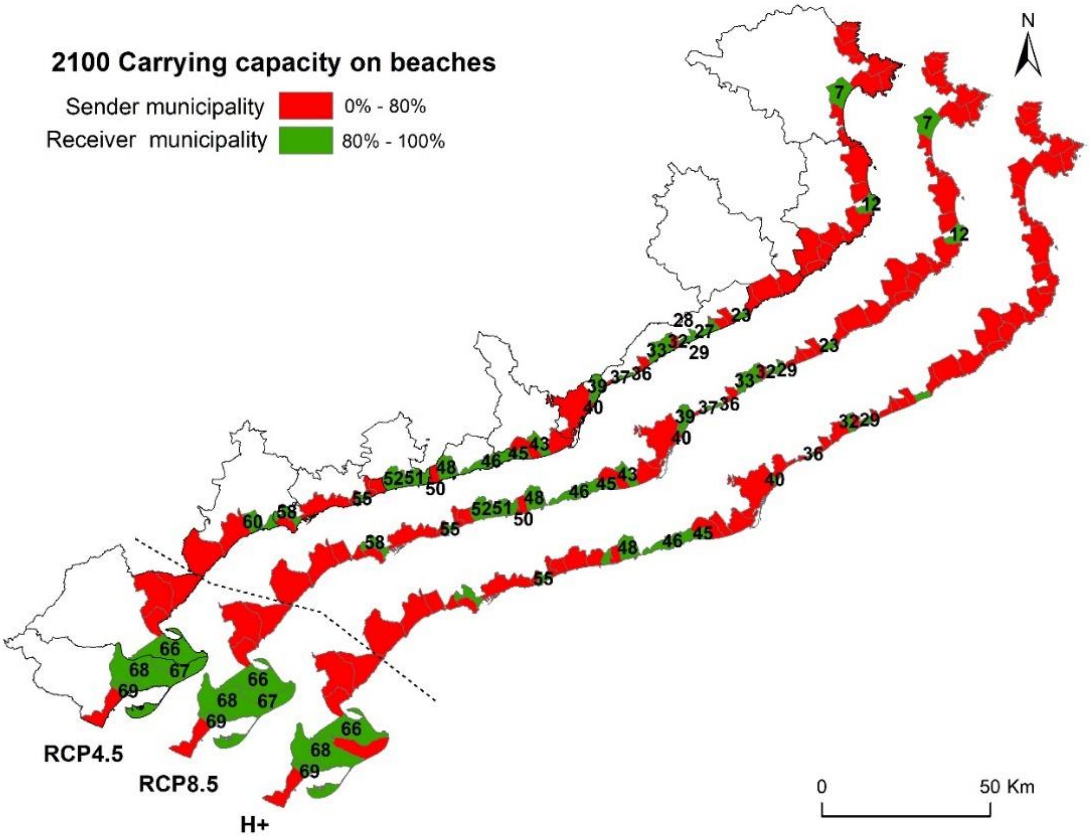


Figure 7.5. Potential sender and receiver municipalities by 2100 at different SLR-scenarios. Discontinuous line indicates Ebro Delta municipalities whose beaches were not considered for potential user distribution. For municipalities' codes, see Table A1 in Annex A.

2. Timing of the action

Fig. 7.6 shows the variation in user distribution based on the PCC relative to the potential demand under different SLR-condition. If the user spatial distribution according to the current PCC is maintained, Catalan beaches will be able to absorb its potential beach demand up to 2050 for both RCPs and up to 2030 for H+. If the triggering point to implement this measure is the 2% decline in GDP, the current distribution will be valid until approximately 2070, 2065 and 2045 for RCP4.5, RCP8.5 and H+, respectively. Discontinuous lines in Fig. 7.6 indicate the capacity for the entire territory of Catalonia, including beaches within Ebro Delta municipalities, in such a way this measure would be extended on average 5 years more if these natural beaches were included. Table C10 in Annex C shows the expected timing for users' distribution promoted by developing new spatial planning policies as an adaptation measure.

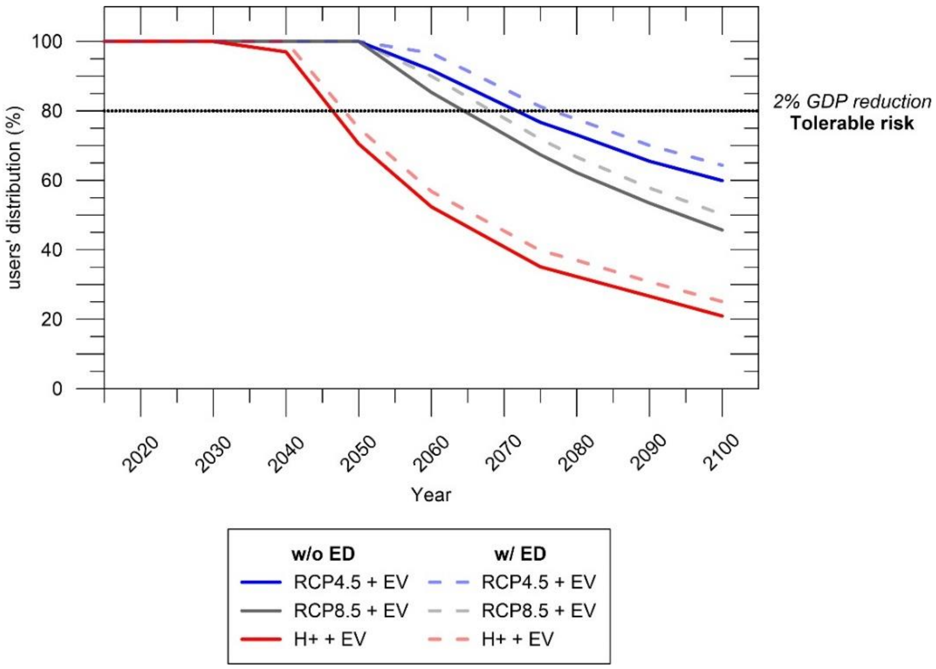


Figure 7.6. Users' distribution in terms of potential demand absorbed by the PCC on Catalan beaches. Discontinuous lines indicate the increase in the distribution capacity by including Ebro Delta (ED) beaches.

7.3.3.4. Discussion

Technological limits. Theoretically, there are no technological limits in this case. The main challenge involved in implementing this measure will be the development of new urban infrastructures and services associated to the recreational use of beaches. In general terms, the larger the number of users, the larger the number of existing services (Jiménez et al., 2007). Not only tourism industry must be developed in receiver areas, but also improvements on infrastructures (roads and connections between areas) and beach services designed to facilitate the use of the beach and make the users' experience comfortable (easy access to the beach, showers, bars, WCs, among others). The main challenge for this strategy is related to the territorial planning of each site, which determines if the development of new infrastructures is possible or not. In this sense, receiver areas must have a soil classification that allows for the urbanization without generating any impact.

Economic barriers. The main and the highest impact of the implementation of this measure is the abandonment of well-stablished areas with local economies strongly linked to coastal tourism (e.g., Costa Brava). However, this option could be an opportunity for less-developed areas by improving the tourism market in those with enough space in their beaches. On average terms, approximately 30% of tourism GDP is generated in Costa Brava but, as seen in Fig. 7.5, their beaches will not be able to support their potential demand at their own at long time projections. Only Castelló d'Empuries and Begur municipalities will present an excess of their PCC with respect to their potential demand to host potential users from other areas under RCP conditions whereas such capacity will be null for the worst-case scenario (H+). The projected variation in its tourism GDP derived from the mobilisation of users in sender municipalities will range between 78-100% by 2100 with respect to 2019 values depending on the SLR considered with a very high economic impact at the local scale (Table 7.3). On the other hand, the most benefited tourism brand from user distribution will be Costa de Barcelona where more than half of the potential receiver municipalities will be located within this brand at any SLR-scenario, although it is not clear that its territory would allow the necessary urban development for the tourism industry given its current level of urbanization. Therefore, its contribution to tourism GDP, approximately 17%, would be increased by developing spatial planning policies and providing resources to promote the use of their beaches. Furthermore, the impact on GDP from sender areas will be less than the other tourism brands (Table 7.3).

Table 7.3. Variation in tourism GDP by 2100 from potential user mobilization in sender municipalities.

Tourism brand	2019 tourism GDP (M €)	Variation from sender municipalities		
		RCP4.5	RCP8.5	H+
Costa Brava	3,893	78%	90%	100%
Costa de Barcelona	2,352	31%	34%	61%
Barcelona city	4,070	85%	87%	95%
Costa Dorada	2,947	57%	66%	83%

Financial barriers. Spatial planning seems to be constrained by accessible finance to develop new areas with enough space on their beaches as well as to compensate losses in those whose beaches are retreating or even collapsing. Furthermore, spatial planning has a critical anticipatory role to play in promoting robust adaptation (Wilson, 2006) in such a way planning new tourism must be proactive (Ryan, 2002). Furthermore, when defining tourism planning policies and developing new tourist areas is important to consider the life cycle and the maturity state of the tourist destinations (Butler, 1980). Specifically for the massive sun-and-beach tourism model, it is recommended to implement re-structuring processes to face the challenges of competitiveness and future sustainability of the tourist activity (Faulkner, 2002; Ivars-Baidal et al., 2013; Medina-Muñoz et al., 2016).

Social conflicts. The implementation of this measure will lead to a considerable socioeconomic change since sender areas would lose their current model of economic development while receiver areas would support a greater one. It is inevitable that any modification in the tourism development induces changes on the social character of the destination. The PCC reduction in sender areas will transform the competitive position and sustainability of coastal tourism with important implications for potential tourism revenues, destination marketing as well as local economies and loss of work positions. Conversely, some conflicts in receiver areas will arise relating overcrowding situations and environmental problems (Burak et al., 2004; Saveriades, 2000), civil complaints about effects on the territory (Hjalager et al., 2020), and even social movements against classical tourism (Milano et al., 2019).

Spatial planning can be used as a tool for a sustainable development if environment, society and economy is considered (Risteskia et al., 2012). The challenge for planning is to ensure the efficient use of the resource (here, beaches) while balancing socio-economic development, cultural heritage and environmental protection.

7.3.4. Concluding remarks

It is worth to mention that coastal tourism is one of the most important industries for the Catalan economy. Presented strategies correspond to two opposite perspectives for managing the coast with the same strategic objective to maintain the carrying capacity of beaches in order to sustain the economic contribution from their recreational use. Through beach nourishment works, it is expected the maintenance of the status quo of beaches whereas the total capacity can be preserved by allowing the distribution of potential users throughout the territory. Furthermore, the type of use done by beachgoers differs among presented strategies. Nourishment is implemented regardless of the type of visitor, tourist or local, representing the total recreational use. However, the spatial distribution strategy compares the reduction in the carrying capacity with the possible influx of beachgoers, focusing more on the tourist component of the recreational function of beaches. As seen previously, both measures present advantages and disadvantages when designing and implementing providing a comparative analysis in terms of technological limits, economic and financial barriers to adaptation and social conflicts.

Technically, the broad experience in nourishment works makes it easier to implement than new spatial planning policies. In fact, artificial nourishment has become the most used action to try to counteract beach erosion along the Catalan coast during the last decades and along worldwide coasts (Cooke et al., 2012; Hanson et al., 2002; Luo et al., 2016). In addition, improvements have been made in the design and execution of projects as well as the exploitation of deeper sand reservoirs. As far as spatial planning strategies is concerned, the apparent lack of technological requirements for promoting the distribution of beachgoers is not real since the development of services is required to facilitate the use of beaches and to satisfy the recreational experience (easy access, showers, WCs, bars, among others) (Jiménez et al., 2007). This will be feasible in receiver areas if and only if re-planning policies are introduced to the development of such recreational infrastructures.

Economically, the maintenance of the current economic contribution is faster through nourishment works by maintaining the current status quo of beaches. Obtained benefits in terms of avoiding losses in tourism GDP are significantly higher than the associated costs (Table 7.2). Furthermore, such costs can be distributed over time through periodic actions. In contrast, despite being highly profitable in potential areas to be developed, the creation of new recreational areas with enough carrying capacity on their beaches will require a very high investment at initial stages.

As far as obtaining funds is concerned, beach nourishment is financed by proper budgetary appropriations by the Central Government because, by Law, the coastal defence and maintenance is strictly its responsibility. Conversely, spatial planning will attract private interest as it means the development of new economic markets. Private provisioning attracts investment when returns are high, such as in coastal tourism and real estate. Showing both strategies can be an alternative to introduce Public-Private Partnerships in financing adaptation in such a way those stakeholders benefiting from the maintenance of the recreational capacity on beaches are pushed to co-finance the responsibility of investing in adaptation.

Finally, from the social standpoint, the spatial planning strategy will carry the greatest impact since the implementation of this measure will affect the local economy leading to a general mobilization while most of the social complaints generated by beach nourishment actions are associated to environmental conservationist complaints.

7.4. Adaptation strategy for the natural use of the coast

7.4.1. Adaptation strategies in low-lying natural areas

Adaptation to climate change is particularly important in low-lying coastal areas threatened by SLR (Hinkel et al., 2014; Nicholls et al., 1999). In fact, there are two main reasons underpinning the need for it: (i) to prevent the loss and degradation of coastal habitats, and consequently, the impacts on society, and (ii) to reduce the increased potential risk to people and assets.

From the natural landscape perspective, the inherent adaptive capacity of coastal habitats, especially wetlands, appear to be large (Kirwan and Megonigal, 2013). Their main adaptation mechanisms involve vertical accretion to keep pace with SLR (Cahoon et al., 1995; Kirwan et al., 2010; Reed, 1995) as well as landward migration for their survival (Enwright et al., 2016). One strategy for enhancing this natural resilience is through innovative nature-based solutions including management realignment as a sustainable adaptation measure to ensure that there is enough space to adapt naturally (Esteves and Williams, 2017). During the last years, there is a growing tendency of giving importance to the role of “building with nature” by promoting sustainable practices in the context of climate change (Jacobs et at., 2009: Luisetti et al., 2011; van Staveren et al., 2014).

Conversely, adaptation in these areas is also driven by the maintenance of the economic development encouraging protection to prevent significant changes to the current structure of the economy (Suckall et al., 2018). Therefore, interaction between land use and economic interests can influence adaptation. This is observable in the Ganges-Brahmaputra-Meghna Delta (Nicholls et al., 2016) where constructing dykes is envisioned to safeguard the economic potential of the area (Ahmed et al., 2017). In fact, the World Bank invested approximately US $400 M to improve polder embankments in Bangladesh with the objective to protect from direct inundation and to improve the agricultural production by reducing saltwater intrusion (World Bank, 2013). Other example can be found in the Mekong Delta where current protection policies shifted to protection strategies based on raising dikes in order to enable the socio-economic development dedicated principally to rice farming (Renaud et al., 2013).

Particularly for our study case areas, these two approaches could be applied to address adaptation. Although their economic contribution to the Catalan GDP is low, essentially related to agriculture, this activity cannot be completely ignored due to its social and cultural component. On the other hand, the studied low-lying areas represent hotspots in terms of natural values and they concentrate the largest contribution to natural capital along the Catalan coast. Therefore, both economy and environmental protection must be considered to designing adaptation strategies at these coastal zones. In what follows, two adaptation alternatives are presented and discussed.

7.4.2. Nature-Based solutions

7.4.2.1. Specific criteria

The objective of this strategy is to provide locally enhanced resilience to SLR in low-lying areas by promoting natural protection by creating natural buffer zones. This implies to generate accommodation space to permit habitat creation/conversion and conservation as SLR generates the inundation of the area. To this end, it is essential to facilitate habitat conversion to promote the value of the ecosystem services provided by these natural areas while maintaining economic activities, mainly agriculture, at higher elevation areas where the risk is low. In this sense, following results obtained in the impact assessment presented in Chapter 4, SLR can be considered an opportunity, with a substantial part of the land (higher elevation areas) being economically profitable at medium-term projections, and the most vulnerable areas (lowest elevation) being susceptible to permit the development of new natural areas. The implementation of this measure assumes the following:

- Managed realignment to reclaim stretches of agricultural land at the most vulnerable area to SLR-flooding (lowest elevation zones).
- Buyout of private properties by the Central Government to incorporate them to the Maritime-Terrestrial Public Domain (MTPD).
- Progressive removal of fixed infrastructures in affected areas to enhance ecosystems connectivity and capacity of landward migration.

7.4.2.2. Methodology

1. Delimitation of potential areas to allow the re-naturalization

With this strategy, the operational target is to allow a progressive inundation to promote the likely conversion of some habitats. The delineation of flood-prone areas under SLR including hydraulic connectivity has been introduced in Chapter 4. This methodology is applied and the inundation is projected by 2100 through successive steps of action phases. Because the inundation extent depends on the SLR-scenario considered, the most unfavourable climate change conditions is presented here given by the RCP8.5 scenario.

2. Definition of action phases

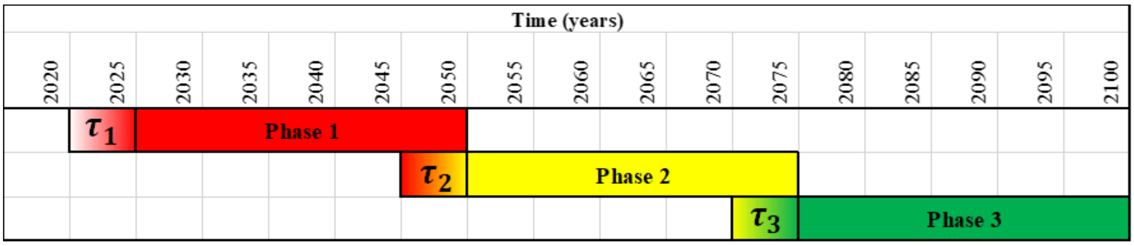
Once the potential areas likely to be affected by SLR are defined, it is established the action phases at which several measures will be implemented to create space for natural dynamic processes. In this work, different time horizons (2050, 2075, and 2100) have been defined for a progressive transformation required for habitat shift.

Given the timescales of adaptation (Hallegate, 2009), managed realignment and land reclamation entail a preparation phase (τ) required for negotiating with the involved stakeholders, land buyouts and expropriations as well as for dismantling fixed barriers. Here, it is assumed 5 years for planning and preparedness, and 25 years between action phases to let nature take its course. This progressive implementation allows for an adaptive management of the strategy to evaluate how it works during a phase and apply corrective actions, if necessary, to the next one.

7.4.2.3. Results

Fig. 7.7 shows the vulnerable areas to SLR-induced flooding in GR, LD and ED and action phases of re-naturalization and managed realignment. The time line of this strategy is represented in Table 7.4 where main implemented actions are summarized.

Table 7.4. Time line and main activities to take during action phases in GR, LD and ED under the RCP8.5 scenario.



	Phase 1			Phase 2			Phase 3		
	GR	LD	ED	GR	LD	ED	GR	LD	ED
Expropriation/purchase of cropland (ha)	86	29	2,129	118	60	5,516	341	204	4,079
Withdrawing of urban infrastructure (ha)	8	1	35	3	3	216	22	4	313

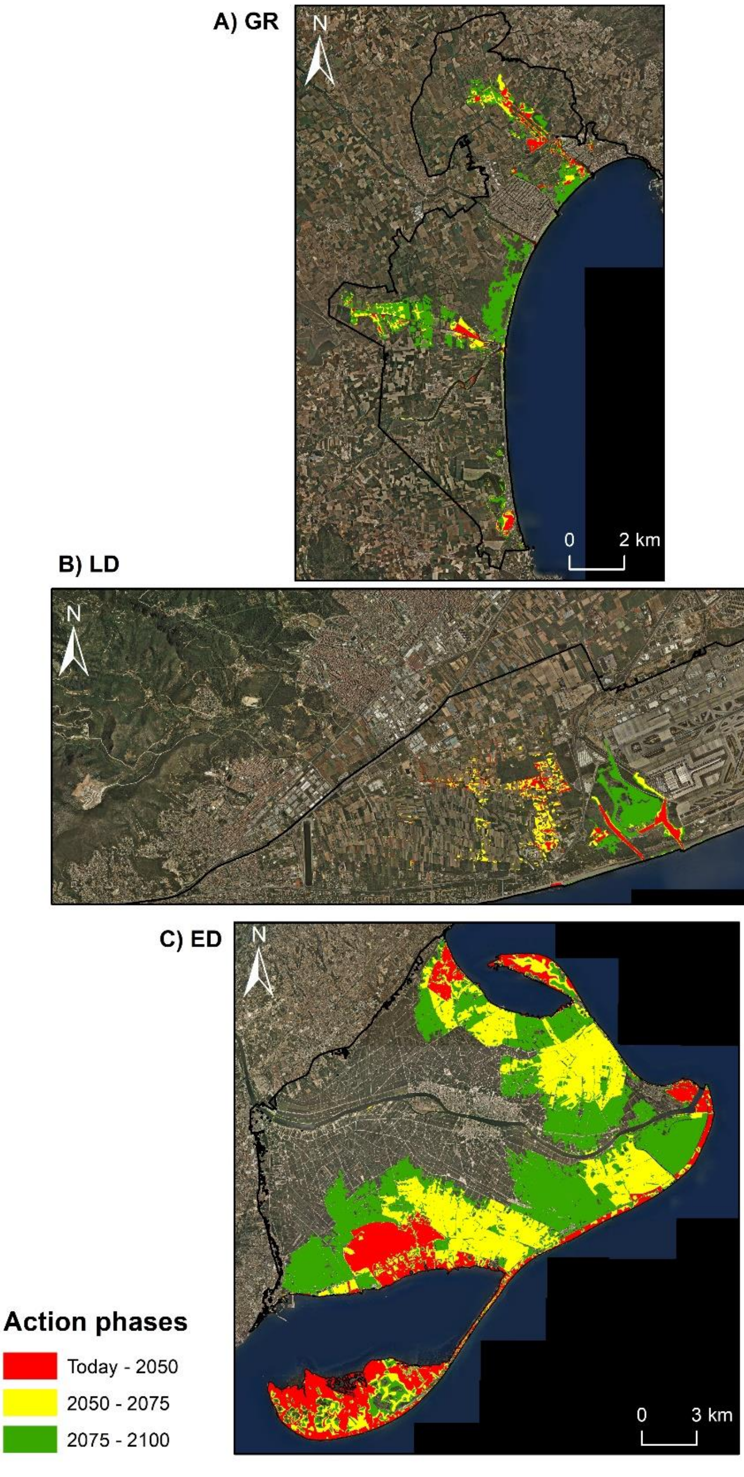


Figure 7.7. Potential areas to implement the nature-based strategy at different action phases in a) GR, b) LD, and c) ED under the RCP8.5 scenario.

- Phase 1: from present to 2050.

During the first five years (2020-2025), it will be required the buyout of approximately 2,245 ha of agricultural land in total. This represents the 2%, 3% and 9% of the current croplands in GR, LD, and ED, respectively. Furthermore, 44 ha of fixed barriers will be removed to favour landward migration of natural ecosystems, which approximately 75% correspond to water ponds and irrigation channels for agriculture. Among analysed low-lying areas, 95% of the total efforts during the first part of implementation (τ_1) are destined to ED.

The natural buffer areas must be ready at 2025 to allow the progressive inundation and the likely habitat conversion.

- Phase 2: from 2050 to 2075.

The preparation to phase 2 (τ_2) will start in 2045 during which approximately 5,700 ha of agricultural lands must be expropriated and incorporated to MTPD. This would imply the additional purchase of 2%, 5% and 24% of current croplands in GR, LD and ED, respectively. In turn, 222 ha of fixed structures will be dismantled, mainly infrastructures to support agricultural activities. As in phase 1, most of the actions to be implemented will be concentrated in the ED (97%).

The natural buffer areas must be ready at 2050 to allow the progressive inundation and habitat conversion.

- Phase 3: from 2075 to 2100.

The preparation to phase 3 (τ_3) will trigger in 2070 giving time to the last negotiations and land purchases during which approximately additional 4,625 ha of croplands should be incorporated to the MTPD. This will be accompanied by the removal of 340 ha of man-made infrastructures which correspond to 70% supporting services to agriculture, 25% small buildings and 5% roads. During this planning phase, although ED remains the main hotspot, the need for these actions becomes noticeable in GR and LD requiring 7% and 4%, respectively, of the total work.

The natural buffer areas must be ready at 2075 to allow the progressive inundation and habitat conversion.

As an example, Fig. 7.8 shows affected areas subjected to managed realignment in the southern part of the ED where, progressively, cropland areas should be expropriated and incorporated to the MTPD, and fixed infrastructures should be removed to generate the space required for horizontal migration and connectivity. The implementation of this strategy requires long-term and strategic planning where managed retreat is gradual by defining setback lines with time scales that preclude the potential increase in risk due to SLR. In addition, this progressive action plan allows for an adaptive management by evaluating the environmental state achieved in each phase in order to implement required actions compatible with habitat recovery, such as the regulation of freshwater inputs to control the salinity stress, an important factor for wetland development (White and Kaplan, 2017).

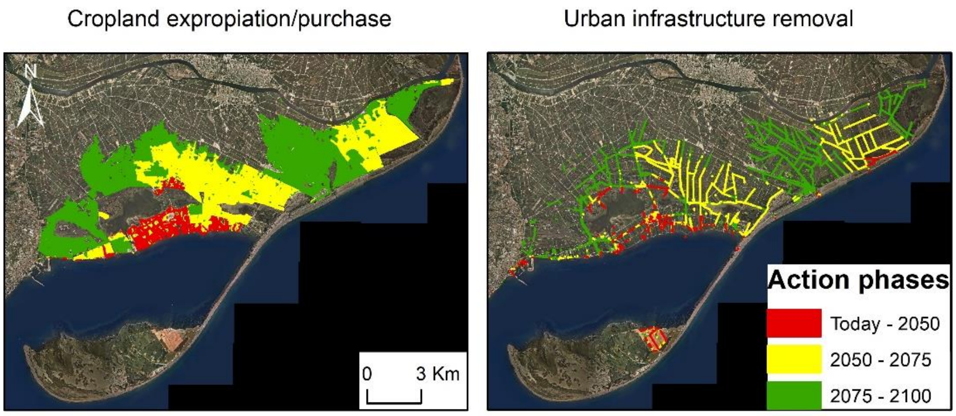


Figure 7.8. Timing for potential actions to implement in the southern Ebro hemidelta under RCP8.5.

7.4.2.4. Discussion

Technological limits. Two important factors limit this strategy: space and time. The more space available between the sea and urbanized areas, the higher the efficiency of the nature-based defence (Temmerman et al., 2013). On the other hand, the time available becomes crucial for habitat adaptation (discussed in Chapter 4). Through this progressive managed realignment, both elements are achieved.

Economic barriers. The implementation of this strategy is suitable in areas with high environmental value under which the common good is quantified in terms of non-market values by ecosystem recovery. Unless provided ecosystem services were not valued by the society, the economic costs will be lower than the expected benefits.

Financial barriers. Compensation, including land purchase, is one of the major limitations of this strategy. The increased provision of financial compensation to local stakeholders, mainly the owners of croplands affected by the managed realignment, is a challenging task (Ledoux et at., 2005). According to the Coastal Law, payments are in charge of the Central Government in such a way that future funding needs will increase as sea level rises whose budgetary allocations should be defined at the early stages of this strategy. To solve financial needs, Central Government could applied for EU funds for environmental conservation and adaptation to climate change.

Social conflicts: Lack of awareness, poor acceptance of local population and government mistrust are among the main constraints to the implementation of this measure. Roca and Villares (2012) analysed social perceptions of managed realignment strategies in the ED revealing a local mistrust of public bodies by their feeling of abandonment from past episodes.

7.4.3. Proposal for actions in the Ebro Delta to protect its integrity and adapt to RSLR

7.4.3.1. Proposed measures

Another alternative is developed from the perspective of protecting economic activities in these areas of which curently there is an example already suggested for the Ebro Delta (Comunitat de Regants de la Dreta del Ebre, 2017). In particular, structural measures combining “grey” and “green” infrastructures are proposed based on three actions (Fig. 7.9):

1. Construction of 50-km dike (1.5-2 m height, 4-5 m width) to protect the delta plain, urban settlements, interior lagoons with high environmental value (Encanyissada, Tancada, Alfacada, Canal Vell, among others) and agricultural land (Fig. 7.9, in red). Along La Marquesa and Alfacada beaches, currently under erosion processes, a setback zone, 150-300 m wide, will be defined to allow an optimal beach width for protection.

2. Re-building of El Fangar and Les Alfaques spit-bars (1-2 m) by sand contributions to maintain the current structure and coastal dynamics. In addition, this action is accompanied by environmental and landscape improvement works in El Trabucador bar (Fig. 7.9, in yellow).

3. Creation of dunes with different configurations to dissipate wave energy and local actions to protect the coast against erosion and shoreline retreat (e.g., sand nourishment in Buda Island and La Marquesa beach) (Fig. 7.4, in green).

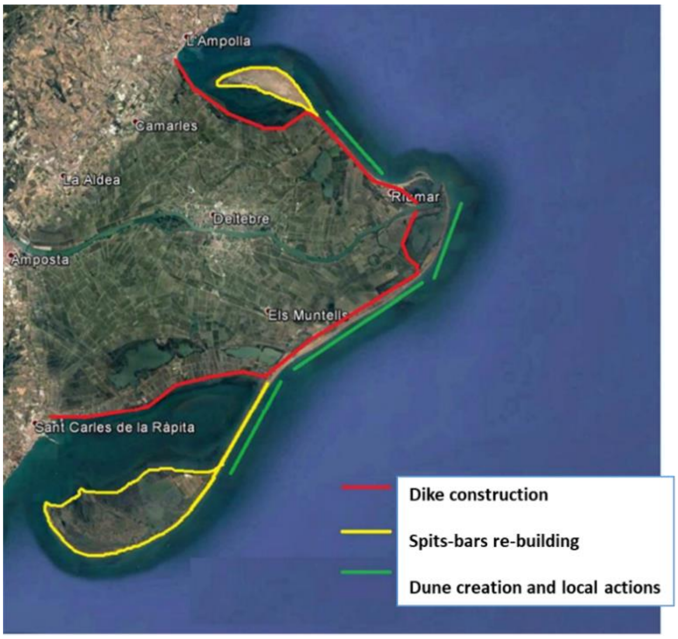


Figure 7.9. Protection strategy suggested for the ED. Adapted from Comunitat de Regants de la Dreta del Ebre (2017).

Furthermore, within the delta protection plan is also proposed the idea of recovering the sediment fluxes from the Ebro River to the delta in order to increase the vertical accretion in the rice fields. To undertake this action, a sediment by-pass system is required to remobilize the material from the reservoirs of the lower catchment area to the river and irrigation network of the ED.

7.4.2.2. Discussion

Technological limits: Although the protection objective from dikes will be achieved in the inner bays, protected areas will be below future water levels affecting the agricultural use of the lowest elevation areas. This action does not avoid the effects of saltwater intrusion in such a way pumping stations will be required increasing future investments. Furthermore, the resources for spits-bar reconstruction (sand and money) are finited and limited restricting the applicability of this action.

Economic barriers. According to this report, an initial cost assessment of these measures reveals implementing costs of €170 M. A detailed analysis is needed to quantify maintenance costs and future investments required.

Financial barriers. Although it is established that the Central Government will finance these measures, the owners of the rice fields should make part of the investment since they are the main beneficiaries from this strategy.

Social conflicts. Building artificial barriers generate mistrust among entities defending the natural heritage due to the lack of a detailed and precise assessment of the possible impacts caused by its construction. In fact, the social study carried out by Fatorić and Chelleri (2012) revealed that most of the interviewed stakeholders from different sectors recommended softer actions for the ED that is most in harmony with the nature.

7.4.4. Concluding remarks

The adaptation of low-lying coastal areas has been designed from a perspective of economic impacts or from natural landscape changes. Here, we synthesized the potential strategies to be applied in natural areas along the Catalan coast.

The protection strategy suggested by local stakeholders is mainly based on traditional engineering measures, such as dyke construction and beach nourishment works, whereas habitat creation and restoration provide an ecologically sound alternative following the concept of building with nature. The delta-sea transitional border will be removed thought the implementation of hard measures under which natural ecosystems will be affected. However, the proposed re-naturalization of the area will be an opportunity to restore and create new areas with high environmental value. In this sense, the construction of any barrier may isolate the coast and sea causing a degradation of vulnerable and important ecosystems as well as interacting with the delta evolution requiring further adaptation (Welch et al., 2017). However, there may be substantial synergies between protection and biodiversity conservation perspectives. The sediment input from the Ebro River can be beneficial not only for rice production (Genua-Olmedo et al., 2016) but also for the survival of some habitats, mainly wetlands (Cahoon et al., 1995; Kirwan et al., 2010; Reed, 1995), to promote vertical accretion and for elevation gain.

Working with nature allows the delta to adapt in a progressive way to new environmental conditions, whereas the main aim of the protection strategy is the maintenance of the status quo of the delta so as not to alter the agricultural production tradition and its associated way of living. Given than the productivity of cropland areas in the lowest elevation zones will be largely affected as sea level rises, with future maintenance costs being progressively higher, the transformation of agricultural areas into wetlands could be more sustainable given the important environmental values of these areas once habitats are restored. An additional factor to consider is that rice production is a subsidized activity in the framework of EU Common Agricultural Policy, whose long-term maintenance is questionable (e.g., Plieninger et al., 2012). Furthermore, the EU Habitats Directive (1992) requires for compensatory measures for projects having a negative impact on Natura 2000 sites, found in our study areas. Rigidizing the coast can cause intertidal habitat loss due to coastal squeeze, so that environmental degradation requires creation of habitats as a compensatory measure, with similar functions as those lost, to ensure the overall coherence of Natura 2000 protection (Defra, 2005; Pontee, 2013).

In terms of who must finance adaptation, the current proposal to protect the ED requires a high investment that directly favour the rice producers' interests. This is why, similarly to beach nourishment, the responsibility for co-financing adaptation should be introduced by Public-Private Partnerships. Nature-based solutions also implies a cost but in this case the entire society is benefitted paying for a public good through environmental benefits provided by habitat restoration, conservation and protection.

Finally, the social dimension of adaptation in natural areas focuses mainly on how to balance environment and economic development, often viewed as competing perspectives. However, the political and cultural dimension highly influence the adaptation decision. Managed realignment entails a large political risk hindering the adoption of this adaptation strategy (Gibbs, 2016) preferring traditional protection engineering measures to maintain the current status quo in terms of livelihoods (Suckall et al., 2018). A better understanding and raising awareness about nature-based solutions is urgently needed to provide an alternative for buffering the impacts of SLR while counteracting many drawbacks of hard infrastructures (Jones et al., 2012).

To sum up, managed realignment in some areas will become unavoidable under the acceleration of SLR. Incorporating potential affected areas to create natural buffer zones can increase the adaptive capacity of these areas and simultaneously decrease the vulnerability of the coastal assets to the impacts of SLR.

Chapter 8

Conclusions

8.1. Summary of main findings and conclusions

In this thesis we have presented a coastal risk framework to assess the impact of SLR-induced erosion and inundation on two of the main functions provided by sedimentary coasts, recreation and natural/environmental. This framework was developed for and applied in the Catalan coast.

Obtained results showed that the Catalan coast is highly vulnerable to erosion due to its current erosive behaviour which will be significantly increased under tested SLR-scenarios. This SLR-enhanced erosion may have drastic consequences for the overall beach recreational carrying capacity, one of the key elements for coastal tourism development. This will result in a decrease in the capacity to provide space and quality for recreation, with an expected significant and growing economic impact in the next decades.

On the other hand, Catalonia has a very low sensitivity to SLR-inundation due to its coastal configuration (i.e., steep beach slopes) except for low-lying areas (Gulf of Roses, Llobregat Delta and Ebro Delta), which concentrate the highest natural values of the Catalan coast. The vulnerability of these areas depends on the configuration of the water-land border, topography, geomorphology, and degree of human impact on the floodplain, being the Ebro Delta the most vulnerable to SLR. In spite of their physical vulnerability, existing habitats have a natural adaptation capacity, which permit to maintain providing ecosystem functions although under a modified landscape.

Once these SLR-induced impacts were evaluated, the status of coastal adaptation to SLR was investigated. First, a diagnosis of the current implementation of adaptation was done, followed by a proposal of suitable adaptation strategies to manage impacts on the Catalan coast. Due to the complementarity of analysed functions, resulting in suitable adaptation strategies have different perspectives. When the management of recreational values is the target, adaptation strategies based on actively maintaining the beach carrying capacity along the Catalan coast are economically effective and technically feasible. On the other hand, in areas of high natural value, adaptation strategies based on enhancing and promoting the natural resilience of coastal habitats to SLR may become the cornerstone for preserving natural values along the Catalan coast.

The main concluding remarks derived from the different sections of this thesis are presented in what follows. As each Chapter was designed to be self-contained, specific conclusions are found in each one and general ones are summarized covering each aspect separately:

Impact of SLR on the recreational function of the coast

- A methodology to assess the effect of SLR on the recreational function has been developed. On the one hand, the physical impact has been assessed in terms of variations in the physical carrying capacity on beaches by SLR-induced shoreline retreat. On the other, the potential impact on the economic contribution of the tourism sector has been evaluated given the importance of this sector to the Catalan GDP.
- The physical carrying capacity on beaches is projected to decrease with significant spatial variations due to the combination of different coastline evolution rates and beach morphology. Costa Barcelona is the most affected under current evolution rates since erosional hotspots are found within this tourism brand (e.g., Maresme comarca).). When SLR is considered, severely affected municipalities will appear within the Costa Brava affecting significantly its potential beach demand
- Costa Brava and Costa Dorada are the tourism brands whose economies strongly depends on tourist activities being, in turn, the most affected by variations in the number of beach users, whose GDP decline would exceed 20% under the worst-case scenario.

Impact of SLR on the natural function of the coast

- A methodology to assess the effect of SLR on the natural function has been developed. On the one hand, the physical impact has been assessed by estimating the expected changes in the surface occupied by most important habitats under different SLR scenarios in low-lying areas of the Catalan coast. On the other, the potential impact on the ecosystem services values has been evaluated given the multiple benefits they provide to society.
- The current development level of the Catalan coast, heavily urbanized as most of the Mediterranean coastline, limits the accommodation space for allowing natural protection. Fixed man-made infrastructures prevent beach rebuilding and landward migration of coastal habitats, as well as controlling the inundation extend especially in the Ebro Delta.
- The Ebro Delta is the most valuable area delivering annually at least €288 M to citizens. By promoting habitat creation to increase coastal resilience in the face of SLR, the benefits provided by coastal ecosystems will not only be maintained in the future but also enhanced as in the Ebro Delta by doubling this value by 2100.

Adaptation to climate change

- A methodological framework to analyse the progress in implementing coastal adaptation has been designed to understand how we are adapting to climate change. Tracking how adaptation is taking place facilitates the assessment of adaptation efforts over time and space.
- Although implemented actions were labelled as adaptation to climate change, some of them have been designed to solve current coastal problems. The misuse of the concept of adaptation measure will tend to the society to be overconfident about adopted actions whereas we are not progressing to real adaptation. To overcome this risk, it is necessary to have a clear roadmap for implementing adaptation measures together with a proper financing structure.
- If the objective is to maintain the recreational use of beaches, adaptation actions should be designed to maintain the future beach carrying capacity in priority areas within a given range in order to sustain the economic contribution of coastal tourism activities.

- If the objective is environmental protection and conservation, the consideration of the inherent resilience of natural areas can allow for open up new adaptation alternatives in which SLR is not only a threat but also an opportunity from the natural standpoint.

8.2. Further research

The research presented in this thesis is a comprehensive assessment of SLR-impact on coastal functions and their consequences. However, different challenges to further complement, improve, and extend this work have been identified:

- To incorporate possible scenarios of coastal tourism as well as variations in the potential tourism demand. External factors such as COVID-19 pandemic influence the economy whose recommendations to maintain interpersonal distance cause scenarios with low users' density in beaches.
- To introduce dynamic models and Bayesian networks to better represent coastal processes at long-term projections.
- To improve the prediction of habitat response to changing conditions.
- To include social perception analysis to understand the level of risk in coastal areas and to address social conflicts that largely influence coastal adaptation.

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Annex A

Recreational function of the coast

Table A1. Administrative units along the Catalan coast (from North to South).

Province	Coastal *comarca*	Municipality
Girona	Alt Empordà	1. Portbou 2. Colera 3. Llançà 4. El Port de la Selva 5. Cadaquès 6. Roses 7. Castelló d'Empùries 8. Sant Pere Pescador 9. L'Escala
	Baix Empordà	10. Torroella de Montgrí 11. Pals 12. Begur 13. Palafrugell 14. Mont-Ras* 15. Palamòs 16. Calonge 17. Castell-Platja d'Aro 18. Sant Feliu de Guìxols 19. Santa Cristina d'Aro
	Selva	20. Tossa de Mar 21. LLoret de Mar 22. Blanes
Barcelona	Maresme	23. Malgrat de Mar 24. Santa Susanna 25. Pineda de Mar 26. Calella 27. Sant Pol de Mar 28. Canet de Mar 29. Arenys de Mar 30. Caldes d'Estrac 31. Sant Vicenç de Montalt 32. Sant Andreu de Llavaneres 33. Mataró 34. Cabrera de Mar 35. Vilassar de Mar 36. Premià de Mar 37. El Masnou 38. Montgat
	Barcelonès	39. Sant Adrià del Besos 40. Badalona 41. Barcelona
	Baix Llobregat	42. El Prat de Llobregat 43. Viladecans 44. Gavà 45. Castelldefels
Tarragona	Garraf	46. Sitges 47. Sant Pere de Ribes* 48. Vilanova i la Geltrú 49. Cubelles
	Baix Penedès	50. Cunit 51. Calafell 52. El Vendrell
	Tarragonès	53. Roda de Barà 54. Creixell 55. Torredembarra 56. Altafulla 57. Tarragona 58. Vila-Seca 59. Salou
	Baix Camp	60. Cambrils 61. Mont-Roig del Camp 62. Vandellòs i l'Hospitalet de l'Infant
	Baix Ebre	63. L'Ametlla de Mar 64. El Perelló 65. L'Ampolla 66. Deltebre
	Montsià	67. Sant Jaume d'Enveja 68. Amposta 69. Sant Carles de la Ràpita 70. Alcanar

* Municipalities not considered as they do not have beaches.

Table A2. Number of stays per coastal comarca in 2019.

Coastal comarca	Tourist	one-day visitors	Second home
Alt Empordà	7,663,000	2,963,010	12,044,765
Baix Empordà	7,663,000	2,963,010	12,044,765
Selva	8,998,000	4,376,137	5,193,850
Maresme	9,159,000	5,688,978	6,350,400
Barcelonès	23,283,000	9,481,631	11,143,008
Baix Llobregat	2,730,000	9,481,631	5,124,125
Garraf	2,226,000	5,688,978	3,378,931
Baix Penedès	1,387,000	4,515,062	9,857,635
Tarragonès	10,972,000	3,792,652	12,599,453
Baix Camp	4,728,000	3,468,889	6,947,856
Baix Ebre	1,053,000	2,370,408	2,165,357
Montsià	524,000	2,431,187	1,705,277

Note: for tourist and second home, these figures correspond to overnight stays.

Table A3. Average daily expenditure (in €) per coastal comarca in 2019.

Coastal comarca	Tourist	one-day visitors	Second home
Alt Empordà	118.1	41.3	36.8
Baix Empordà	118.1	41.3	36.8
Selva	118.1	41.3	36.8
Maresme	121.0	42.3	36.8
Barcelonès	176.7	61.8	36.8
Baix Llobregat	150.0	52.5	36.8
Garraf	155.6	54.4	36.8
Baix Penedès	120.0	42.0	36.8
Tarragonès	120.0	42.0	36.8
Baix Camp	120.0	42.0	36.8
Baix Ebre	111.2	38.9	36.8
Montsià	111.2	38.9	36.8

Table A4. Tourism expenditure (in M €) per coastal comarca in 2019.

Coastal comarca	Tourist	one-day visitors	Second home	TOTAL
Alt Empordà	700	128	502	1,329
Baix Empordà	905	122	443	1,470
Selva	1,063	181	191	1,434
Maresme	1,109	241	233	1,583
Barcelonès	4,114	586	410	5,110
Baix Llobregat	410	497	188	1,095
Garraf	346	310	124	780
Baix Penedès	167	190	362	718
Tarragonès	1,317	159	463	1,939
Baix Camp	568	146	255	969
Baix Ebre	117	92	80	289
Montsià	58	95	63	215
TOTAL	10,873	2,745	3,314	16,933

Table A5. Physical Carrying capacity (PCC) per coastal comarcas at different time projections under current evolution rates (EV) and SLR-scenarios.

Coastal comarcas	2015	2050				2075				2100			
		EV	RCP4.5 + EV	RCP8.5 + EV	H+ + EV	EV	RCP4.5 + EV	RCP8.5 + EV	H+ + EV	EV	RCP4.5 + EV	RCP8.5 + EV	H+ + EV
Alt Empordà	18,699	17,122	14,117	13,661	10,849	16,070	11,622	10,890	5,771	15,400	8,633	6,190	0
Baix Empordà	18,030	16,819	13,931	13,260	7,922	14,739	8,072	5,938	519	12,170	3,612	1,535	103
Selva	20,492	13,895	9,145	8,261	2,391	12,362	4,621	2,988	0	10,933	2,575	344	0
Maresme	16,987	10,846	9,429	9,172	7,485	9,285	8,155	7,635	3,882	9,028	7,411	5,672	2,583
Barcelonès	27,225	21,323	17,469	16,727	12,309	17,894	12,554	11,231	7,198	15,856	10,521	9,287	3,866
Baix Llobregat	23,645	22,670	20,893	20,350	15,859	21,208	15,411	14,390	12,436	18,394	14,115	13,489	12,208
Garraf	34,860	32,788	26,702	25,655	18,811	30,093	20,984	19,217	15,666	28,031	18,962	16,812	13,712
Baix Penedès	38,961	28,337	25,533	24,874	18,658	26,367	17,718	15,589	6,220	22,593	13,162	11,547	2,613
Tarragonès	22,844	19,513	16,258	15,742	11,198	17,490	12,676	10,911	6,216	16,094	10,077	8,151	3,708
Baix Camp	47,956	37,592	26,204	24,108	9,829	28,354	15,154	11,706	2,599	22,711	10,921	4,908	1,783
Baix Ebre	22,471	12,039	6,122	6,032	5,199	8,671	5,080	5,029	3,854	7,337	4,563	3,854	3,611
Montsià	27,995	21,481	12,266	10,811	8,433	13,943	8,876	8,359	8,359	13,639	8,359	8,359	6,698

Annex B

Natural function of the coast

Table B1. Land cover types and main habitats found in the study areas.

<table>
<tr><th rowspan="2">Category</th><th rowspan="2">Land cover</th><th colspan="3">Main habitats</th></tr>
<tr><th>GR</th><th>BL</th><th>ED</th></tr>
<tr><td rowspan="2">Urban</td><td rowspan="2">Urban areas
Buildings
Parking areas
Urban green areas
Roads
Infrastructures</td><td colspan="3">Urban and industrial areas, including the associated ruderal vegetation</td></tr>
<tr><td colspan="3">Urbanized areas, with important clearings of natural vegetation</td></tr>
<tr><td rowspan="2">Barren</td><td rowspan="2">Cliffs, rocky outcrops.
Bare, burned, eroded grounds
Extraction and discharge areas</td><td colspan="3">Undeveloped urban areas</td></tr>
<tr><td colspan="3">Abandoned cultivated areas</td></tr>
<tr><td>Salt mine</td><td>Salt mine</td><td colspan="2">Non-existent</td><td>Salt mine and industrial salt ponds</td></tr>
<tr><td rowspan="3">Cropland</td><td rowspan="3">Cultivated areas</td><td>Intensive herbaceous crops different from rice (cereals, fodder)</td><td rowspan="3">Intensive herbaceous crops different from rice (orchards and garden center)</td><td rowspan="3">Rice fields</td></tr>
<tr><td>Fruit trees</td></tr>
<tr><td>Vineyards</td></tr>
<tr><td>Grassland</td><td>Scrubland
Shrub land
Pasture and meadow</td><td>Lowland harvesting fields (mainly Gaudinia fragilis)</td><td colspan="2">Lowland hayfields</td></tr>
<tr><td rowspan="2">Temperate forest</td><td rowspan="2">Various (conifer, deciduous, evergreen trees)</td><td rowspan="2">Riverside woodlands</td><td>Pinewoods (Pinus pinea) and understory</td><td rowspan="2">Riverside woodlands</td></tr>
<tr><td>Residual dunes with pine trees (Pinus pinea, Pinus pinaster)</td></tr>
<tr><td rowspan="2">Beach and dunes</td><td rowspan="2">Beach, dunes and sandy areas</td><td colspan="3">Sandy beaches</td></tr>
<tr><td colspan="3">Dunes and dune slacks</td></tr>
<tr><td rowspan="3">Coastal vegetation</td><td rowspan="3">Shrubby and herbaceous communities on salt or gypsaceous soils</td><td colspan="3">Salicornia sp. Swards</td></tr>
<tr><td colspan="3">Junciform-leaved Spartina versicolor grassland of coastal sand muds</td></tr>
<tr><td colspan="3">Juncus maritimus beds of coastal and inland long-inundated, brackish depressions</td></tr>
<tr><td rowspan="3">Wetland</td><td>Freshwater marsh</td><td colspan="2">Non-existent</td><td>Lowland Cladium mariscus beds of riversides</td></tr>
<tr><td rowspan="2">Brackish marsh</td><td colspan="3">Reed beds</td></tr>
<tr><td>Bulrush beds (Scirpus spp.)</td><td>Cane formation along water courses</td><td>Bulrush beds (Scirpus spp.)</td></tr>
<tr><td rowspan="3">Coastal lagoon</td><td>Freshwater ponds</td><td colspan="3">Standing fresh waters</td></tr>
<tr><td rowspan="2">Saltwater/brackish lagoons</td><td colspan="3">Vegetated/non-vegetated lagoon</td></tr>
<tr><td colspan="2">Non-existent</td><td>Mud and sand flats</td></tr>
</table>

Table B2. Projected surface (ha) under the TDA and CA for different SLR scenarios at 2050 and 2100 in the GR. Note: the final surface for coastal vegetation and wetland areas under the CA will be the sum of current not-affected area and the new converted areas to halophyte vegetation and transitional wetlands, respectively.

Habitat type	current surface (ha)	TDA					CA				
		2050		*2100*			*2050*		*2100*		
		RCP 4.5 RCP 8.5	H+	RCP4.5	RCP8.5	H+	RCP 4.5 RCP 8.5	H+	RCP4.5	RCP8.5	H+
Urban	1,025	1,018	1,013	1,010	991	507	1,018	1,015	1,012	992	507
Barren	73	72	71	70	67	45	134	216	309	457	399
Salt mine	-	-	-	-	-	-	-	-	-	-	-
Cropland	5,435	5,433	5,420	5,411	5,372	4,248	5,349	5,230	5,109	4,889	3,217
Grassland	564	557	550	537	525	345	557	541	536	517	330
Temperate forest	275	273	271	269	264	194	268	264	262	257	180
Coastal vegetation	38	36	34	32	28	9	45	75	84	108	695
Wetlands	792	738	687	595	488	66	767	737	720	563	234
Beach and dunes	126	101	78	65	46	7	121	101	91	74	36
Coastal lagoons	74	66	66	29	19	3	114	165	205	448	2,601

Table B3. Projected surface (ha) under the TDA and CA for different SLR scenarios at 2050 and 2100 in the LD. Note: the final surface for coastal vegetation and wetland areas under the CA will be the sum of current not-affected area and the new converted areas to halophyte vegetation and transitional wetlands, respectively.

Habitat type	current surface (ha)	TDA					CA				
		2050		*2100*			*2050*		*2100*		
		RCP 4.5 RCP 8.5	H+	RCP4.5	RCP8.5	H+	RCP 4.5 RCP 8.5	H+	RCP4.5	RCP8.5	H+
Urban	1,508	1,506	1,503	1,503	1,498	1,370	1,507	1,504	1,503	1,499	1,370
Barren	343	342	342	342	339	296	369	425	473	603	436
Salt mine	-	-	-	-	-	-	-	-	-	-	-
Cropland	1,114	1,114	1,114	1,114	1,111	415	1,085	1,025	971	821	162
Grassland	474	470	467	465	453	293	466	459	450	437	259
Temperate forest	231	230	229	227	223	104	230	226	223	211	80
Coastal vegetation	53	53	53	52	52	25	39	33	40	50	147
Wetlands	256	254	248	236	214	33	258	254	246	230	175
Beach and dunes	113	102	90	84	72	19	101	85	78	61	18
Coastal lagoons	77	53	51	41	32	6	79	90	101	142	1,303

Table B4. Projected surface (ha) under the TDA and CA for different SLR scenarios at 2050 and 2100 in the ED. Note: the final surface for coastal vegetation and wetland areas under the CA will be the sum of current not-affected area and the new converted areas to halophyte vegetation and transitional wetlands, respectively.

Habitat type	current surface (ha)	TDA					CA				
		2050		*2100*			*2050*		*2100*		
		RCP 4.5 RCP 8.5	H+	RCP4.5	RCP8.5	H+	RCP 4.5 RCP 8.5	H+	RCP4.5	RCP8.5	H+
Urban	2,333	2,275	2,033	1,942	1,769	1,093	2,298	2,082	1,953	1,769	1,093
Barren	350	331	309	229	276	145	337	316	302	276	145
Salt mine	90	29	16	13	8	0	29	16	13	8	0
Cropland	22,695	21,724	16,983	14,909	11,713	3,610	20,566	15,050	13,361	10,972	3,207
Grassland	271	257	226	216	191	111	247	219	211	183	112
Temperate forest	56	53	41	37	31	14	44	38	36	28	14
Coastal vegetation	871	561	390	330	248	18	2,106	3,205	2,016	988	413
Wetlands	1,198	712	421	325	84	5	1,499	1,537	1,535	940	308
Beach and dunes	1,878	1,014	481	357	203	36	1,618	1,416	1,341	1,207	799
Coastal lagoons	2,711	1,018	329	250	142	12	3,508	8,146	11,148	15,325	24,649

Table B5. List of monetary values per habitats and services.

Habitat type	Ecosystem service	Method*	Value (2020 €/ha·yr)	Source
Urban Greenspace	Gas/climate regulation	AC	451	Mcpherson 1992
		AC	2,257	Mcpherson 1992
		DM	69	Mcpherson et al. 1998
			926	
	Water regulation	AC	17	Mcpherson 1992
			17	
	Aesthetic and recreation	CV	9,540	Tyrvainen 2001
		CV	3,245	Tyrvainen 2001
		CV	4,804	Tyrvainen 2001
			5,863	
Cropland	Erosion control	RC	175	Pimentel et al. 1995
		RC	66	Pimentel et al. 1995
			120	
	Soil formation	RC	278	Pimentel et al. 1995
			278	
	Pollination	AC	30	Robinson et al. 1989
		DM	13	Southwick and Southwick 1992
		VT	21	Costanza et al. 1997
			21	
	Biological control	VT	35	Costanza et al. 1997
			35	
	Habitat/refugia	CV	3,419	Christie et al. 2004
		CV	1,153	Christie et al. 2004
			2,286	
	Aesthetic and recreation	CV	71	Bergstrom et al. 1985
		CV	11	Alvarez-Farizo 1999
			41	
Grassland	Gas/climate regulation	DM	10	Costanza et al. 1997
		VT	2	Sala and Paruelo 1997
		AC	1	Sala and Paruelo 1997
		DM	376	Sala and Paruelo 1997
		CV	122	Ministerie van LNV 2006
			102	
	Water regulation	VT	6	Costanza et al. 1997
			6	
	Erosion control	DM	38	Barrow 1991
		CV	41	Costanza et al. 1997
		VT	165	Sala and Paruelo 1997
		AC	53	Ministerie van LNV 2006
			74	
	Soil formation	DM	17	Pimentel et al. 1997
		VT	2	Costanza et al. 1997
			9	
	Waste management	RC	149	Ministerie van LNV 2006
		RC	14	Ministerie van LNV 2006
		VT	121	Costanza et al. 1997
			95	
	Pollination	VT	36	Costanza et al. 1997
			36	
	Biological control	VT	33	Costanza et al. 1997
			33	
	Aesthetic and recreation	HP	60	Brookshire et al. 1982
		VT	2	Costanza et al. 1997

		CV	2	Alvarez-Farizo 1999
		DM	31	Ministerie van LNV 2006
		CV	191	Barkmann and Zsciegner 2010
		CV	599	Barkmann and Zsciegner 2010
			148	
Temperate forest	Gas/climate regulation	MP	13	Nordhaus 1993
		MP	91	Nordhaus 1993
		MP	19	Nordhaus 1993
		MP	2	Nordhaus 1993
		MP	135	Reilly and Richards 1993
		MP	116	Reilly and Richards 1993
		MP	55	Reilly and Richards 1993
		MP	39	Reilly and Richards 1993
		MP	52	Frankhauser 1994
		MP	110	Frankhauser 1994
		MP	47	Frankhauser 1994
		MP	45	Maddison 1995
		MP	64	Schauer 1995
		MP	876	Schauer 1995
		MP	556	Azar and Sterner 1996
		MP	28	Azar and Sterner 1996
		MP	82	Azar and Sterner 1996
		MP	182	Azar and Sterner 1996
		MP	77	Hope and Maul 1996
		MP	55	Plambeck and Hope 1996
		MP	1,153	Plambeck and Hope 1996
		MP	17	Norhaus and Yang 1996
		MP	121	Costanza et al. 1997
		MP	23	Norhaus and Popp 1997
		MP	17	Norhaus and Popp 1997
		AC	36	Pimentel et al. 1997
		MP	107	Roughgarden and Schneider 1999
		MP	157	Tol 1999
		MP	831	Tol 1999
		MP	71	Tol and Downing 2000
		MP	45	Tol and Downing 2000
		MP	204	Tol and Downing 2000
		MP	55	Tol and Downing 2000
		MP	215	Tol and Downing 2000
		MP	2	Tol and Downing 2000
		VT	298	CBD 2001
		MP	60	Newell and Pizer 2003
		MP	41	Newell and Pizer 2003
		VT	30	Mates and Reyes 2004
			157	
	Water Supply	TC	25	Loomis 1998
		RC	870	Postel and Thompson 2005
			447	
	Erosion control	CV	136	Costanza et al.,1997
			136	
	Soil formation	VT	13	Costanza et al. 1997
			13	
	Waste management	VT	121	Costanza et al. 1997
		VT	24	CBD 2001
		RC	19	De la Cruz and Benedicto 2009
			55	
	Pollination	RC	446	Hougner et al. 2006
			446	

	Biological control	VT	6	Costanza et al. 1997
			6	
	Habitat/refugia	CV	8	Shafer et al. 1993
		CV	8,926	Garrord and Willis 1997
		CV	41	Garrord and Willis 1997
		CV	5,259	Garrord and Willis 1997
		CV	11	Haener and Adamowicz 2000
		CV	1,173	Kenyon and Nevin 2001
		CV	363	Amigues et al. 2002
		CV	4,540	Amigues et al. 2002
			2,540	
	Genetic resources	CV	176	Walsh et al. 1984
		CV	22	Costanza et al. 1997
		VT	35	CBD 2001
		VT	85	CBD 2001
		VT	24	Phillips et al. 2008
			68	
	Aesthetic and recreation	CV	2	Prince and Ahmed 1989
		TC	2	Willis 1991
		TC	77	Willis 1991
		TC	33	Willis 1991
		TC	13	Willis 1991
		TC	347	Willis 1991
		TC	347	Willis and Garrord 1991
		CV	1,495	Bishop 1992
		CV	1,335	Bishop 1992
		CV	1,264	Shafer et al. 1993
		CV	28	Maxwell 1994
		CV	397	Bennet et al. 1995
		TC	350	Bellu and Cistulli 1997
		VT	49	Costanza et al. 1997
		VT	97	CBD 2001
		DM	12	Phillips et al. 2008
		TC	10	De la Cruz and Benedicto 2009
		VT	3	De la Cruz and Benedicto 2009
			307	
	Cultural and spiritual	VT	2	Costanza et al. 1997
		TC	1	De la Cruz and Benedicto 2009
			2	
Beach and dunes	Disturbance regulation	HP	92,889	Pompe and Rinehart 1995
		HP	57,306	Parson and Powell 2001
			75,097	
	Aesthetic and recreation	HP	361	Edwards and Gable 1991
		CV	56,937	Silberman et al. 1992
		TC	104,218	Kline and Swallow 1998
		HP	1,996	Taylor and Smith 2000
			40,878	
	Cultural and spiritual	HP	66	Taylor and Smith 2000
			66	
Coastal Vegetation**	Disturbance regulation	AC	146	Rein 1999
		AC	339	Rein 1999
			242	
	Water supply	CV	36	Oster 1977
		CV	518	Gramlich 1977
		HP	11	Rich and Moffitt 1982
		TC	17	Kahn and Buerger 1994
		CV	11,275	Danielson et al. 1995
		CV	4,939	Berrens et al. 1996

		AC	267	Rein 1999
			2438	
	Aesthetic and recreation	HP	3,178	Thibodeau and Ostro 1981
		CV	19	Greenly et al. 1981
		HP	84	Amacher et al. 1989
		CV	5,388	Sander et al. 1999
		CV	484	Lant et al. 1990
		CV	3,689	Whitehead 1990
		CV	3,458	Duffield et al. 1992
		CV	2,448	Duffield et al. 1992
		CV	4,140	Hayes et al. 1992
		HP	118	Kulshreshtha and Gillies 1993
		VT	716	Kosz 1996
		DM	191	Rein 1999
		TC	82	Mahan et al. 2000
		VT	716	Schuyt and Brander 2004
		VT	470	Schuyt and Brander 2004
		VT	619	Schuyt and Brander 2004
		DM	1,826	Everard and Jevons 2010
			1,625	
	Cultural and spiritual	CV	11	Greenly et al. 1981
			11	
Coastal wetlands and lagoons ***	Disturbance regulation	AC	5	Farber 1987
		AC	3	Farber and Costanza 1987
		AC	58	Farber and Costanza 1987
		AC	993	Costanza et al. 1989
		VT	2558	Costanza et al. 1997
		RC	277	Ledoux 2003
			649	
	Waste management	VT	14,697	Gosselink et al. 1974
		RC	8,357	De Groot 1992
		AC	45,593	Breaux et al. 1995
		AC	300	Breaux et al. 1995
		AC	4,402	Breaux et al. 1995
		VT	9,311	Costanza et al. 1997
			13,777	
	Habitat/refugia	MP	1,018	Batie and Wilson 1978
		DM	16	Lynne et al. 1981
		AC	2	Farber and Costanza 1987
		DM	104	Coreil 1993
		FI	1,512	Bell 1997
		VT	234	Costanza et al. 1997
		FI	2,272	Johnston et al. 2002
		CM	31	Nunes et al. 2004
			649	
	Aesthetic and recreation	VT	2,815	Gosselink et al. 1974
		CV	2,781	Gupta and Foster 1975
		HP	152	Anderson and Edwards 1986
		TC	38	Farber and Costanza 1987
		TC	25	Farber 1988
		DM	2,251	Bell 1989
		TC	34	Costanza et al. 1989
		CV	242	Bergstrom et al. 1990
		DM	457	Hickman 1992
		DM	1,055	Hickman 1993
		VT	298	Green and Soderqvist 1994

	VT	6,333	Green and Soderqvist 1994
	CV	40	Farber 1996
	FI	44,674	Bell 1997
	FI	6,773	Bell 1997
	VT	1,348	Costanza et al. 1997
		4,332	
Cultural and spiritual	CV	496	Anderson and Edwards 1986
		496	

* Non-market economic valuation methods are: (VT) Value transfer; (DM) Direct market; (AC) Avoided cost; (RC) Replacement cost; (TC) Travel cost; (HP) Hedonic price; (CV) Contingent valuation; (MP) Marginal product, (FI) Factor Income; (CM) Choice modelling.

** ESV for coastal vegetation areas correspond to riparian landscapes due to ecological characteristics and spatial distribution.

*** ESV for coastal wetlands areas correspond to saltwater and tidal marsh areas. There is no differentiation between wetland and coastal lagoon areas.

Tabla B6. Summary of the bundle of ecosystem services per habitat (values in €/ha·yr, 2020 price levels).

Habitat type	N	Total average ESV	Total median values	Total St.Dev. values	Total minimum value	Total maximum values
Urban greenspace	7	6,806	5,272	4,447	3,331	11,814
Barren	0	0	0	0	0	0
Salt mine	0	0	0	0	0	0
Cropland	11	2,781	2,781	1,731	1,556	4,008
Grassland	23	503	322	554	132	1,381
Temperate forest	81	4,177	1,978	4,818	680	13,344
Beach and dunes	7	116,041	104,629	74,905	57,733	197,173
Coastal vegetation	27	4,316	1,236	6,159	187	17,013
Coastal wetlands and lagoons	37	19,903	10,422	29,161	826	95,593

Table B7. Annual flow of non-market value of ES (€/ha·yr in 2020) under the TDA and CA for different SLR scenarios at 2050 and 2100 in the GR. Notes: the aesthetic and recreational value for beach and dunes was omitted. A reduction factor was applied for ESV flow estimations for those modified wetlands and coastal lagoons under the CA.

Habitat type	current conditions	TDA					CA				
		2050		2100			2050		2100		
		RCP 4.5 RCP 8.5	H+	RCP4.5	RCP8.5	H+	RCP 4.5 RCP 8.5	H+	RCP4.5	RCP8.5	H+
Urban greenspace	1,546,771	1,541,531	1,527,374	1,514,715	1,415,688	773,882	1,541,463	1,534,044	1,525,400	1,422,630	773,746
Barren	0	0	0	0	0	0	0	0	0	0	0
Salt mine	0	0	0	0	0	0	0	0	0	0	0
Cropland	15,114,735	15,109,173	15,073,020	15,047,991	14,939,532	11,813,688	14,875,569	14,544,630	14,208,129	13,596,309	8,946,477
Grassland	283,692	280,171	276,650	270,111	264,075	173,535	280,171	272,123	269,608	260,051	165,990
Temperate forest	1,148,675	1,140,321	1,131,967	1,123,613	1,102,728	810,338	1,119,436	1,102,728	1,094,374	1,073,489	751,860
Coastal vegetation	164,008	155,376	146,744	138,112	120,848	38,844	194,220	323,700	362,544	466,128	2,999,620
Wetlands	15,763,176	14,688,414	13,673,361	11,842,285	9,712,664	1,313,598	14,981,983	14,131,130	13,733,070	10,041,064	2,119,670
Beach and dunes	9,470,538	7,591,463	5,862,714	4,885,595	3,457,498	526,141	9,094,723	7,591,463	6,839,833	5,562,062	2,705,868
Coastal lagoons	1,472,822	1,313,598	1,313,598	577,187	378,157	59,709	2,189,330	3,102,878	3,819,386	8,172,172	46,732,244

Table B8. Annual flow of non-market value of ES (€/ha·yr in 2020) under the TDA and CA for different SLR scenarios at 2050 and 2100 in the LD. Notes: the aesthetic and recreational value for beach and dunes was omitted. A reduction factor was applied for ESV flow estimations for those modified wetlands and coastal lagoons under the CA.

Habitat type	current conditions	TDA					CA				
		2050		2100			2050		2100		
		RCP 4,5 RCP 8,5	H+	RCP4,5	RCP8,5	H+	RCP 4,5 RCP 8,5	H+	RCP4,5	RCP8,5	H+
Urban greenspace	1,987,352	1,987,080	1,986,127	1,986,127	1,985,378	1,783,172	1,987,080	1,986,195	1,986,127	1,985,719	1,783,172
Barren	0	0	0	0	0	0	0	0	0	0	0
Salt mine	0	0	0	0	0	0	0	0	0	0	0
Cropland	3,098,034	3,098,034	3,098,034	3,098,034	3,089,691	1,154,115	3,017,385	2,850,525	2,700,351	2,283,201	450,522
Grassland	238,422	236,410	234,901	233,895	227,859	147,379	234,398	230,877	226,350	219,811	130,277
Temperate forest	964,887	960,710	956,533	948,179	931,471	434,408	960,710	944,002	931,471	881,347	334,160
Coastal vegetation	228,748	228,748	228,748	224,432	224,432	107,900	168,324	142,428	172,640	215,800	634,452
Wetlands	5,095,168	5,055,362	4,935,944	4,697,108	4,259,242	656,799	5,075,265	4,965,799	4,746,866	4,323,927	1,990,300
Beach and dunes	8,493,419	7,666,626	6,764,670	6,313,692	5,411,736	1,428,097	7,591,463	6,388,855	5,862,714	4,584,943	1,352,934
Coastal lagoons	1,532,531	1,054,859	1,015,053	816,023	636,896	119,418	1,566,366	1,761,416	1,958,455	2,690,886	23,481,559

Table B9. Annual flow of non-market value of ES (€/ha·yr in 2020) under the TDA and CA for different SLR scenarios at 2050 and 2100 in the ED. Notes: the aesthetic and recreational value for beach and dunes was omitted. A reduction factor was applied for ESV flow estimations for those modified wetlands and coastal lagoons under the CA.

Habitat type	current conditions	TDA						CA					
		2050		2100				2050		2100		
		RCP 4,5 RCP 8,5	H+	RCP4,5	RCP8,5	H+		RCP 4,5 RCP 8,5	H+	RCP4,5	RCP8,5	H+
Urban greenspace	1,531,350	1,509,231	1,456,484	1,434,909	1,361,813	786,774		1,514,879	1,475,064	1,436,338	1,361,813	786,774
Barren	0	0	0	0	0	0		0	0	0	0	0
Salt mine	0	0	0	0	0	0		0	0	0	0	0
Cropland	63,114,795	60,414,444	47,229,723	41,461,929	32,573,853	10,039,410		57,194,046	41,854,050	37,156,941	30,513,132	8,918,667
Grassland	136,313	129,271	113,678	108,648	96,073	55,833		124,241	110,157	106,133	92,049	56,336
Temperate forest	233,912	221,381	171,257	154,549	129,487	58,478		183,788	158,726	150,372	116,956	58,478
Coastal vegetation	3,759,236	2,421,276	1,683,240	1,424,280	1,070,368	77,688		9,089,496	13,832,780	8,701,056	4,264,208	1,782,508
Wetlands	23,843,794	14,170,936	8,379,163	6,468,475	1,671,852	99,515		19,654,213	15,977,133	14,160,985	5,946,021	1,592,240
Beach and dunes	141,156,114	76,215,282	36,153,403	26,833,191	15,258,089	2,705,868		121,613,734	106,430,808	100,793,583	90,721,741	60,055,237
Coastal lagoons	53,957,033	20,261,254	6,548,087	4,975,750	2,826,226	238,836		68,195,639	151,236,926	204,982,987	279,740,646	446,368,562

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Annex C

Adaptation to climate change

Table C1. LIFE projects included in this work.

	Priority area	Project	Location	Period	Code CAS	Budget in M € (% UE)
LIFE Environment	Environment and resource efficiency	Adaptation and mitigation measures to climate change in the Ebro Delta (*LIFE Ebro Admiclim*)	Catalonia	2014-2018	21	2.26 (50%)
		Integrated management of three artificial wetlands in compliance with the Water Framework, Bird and Habitat Directives (*LIFE ALBUFERA*)	Valencia	2013-2016	6	1.45 (50%)
	Nature and Biodiversity	De-urbanizing and recovering the ecological function of the coastal system of La Pletera (*LIFE PLETERA*)	Catalonia	2014-2018	6	2.53 (75%)
		Habitat restoration and management in two coastal lagoons of the Ebro Delta: Alfacada y Tancada (*LIFE DELTA-LAGOON)*	Catalonia	2010-2017	6	3.05 (50%)
		In situ and Ex situ innovative combined techniques for coastal dune habitats restoration in SCIs on Northern Spain (*LIFE+ARCOS*)	Asturias Cantabria Basque Country	2014-2018	4	1.33 (70%)
		Preservation and improvement in priority habitats on the Andalusian coast (*LIFE CONHABIT*)	Andalusia	2014-2019	25	2.65 (60%)
		Integration of human activities in the conservation objectives of the Natura 2000 Network in the littoral of Cantabria (*CONVIVE LIFE*)	Cantabria	2015-2019	6	1.33 (60%)
	Environmental Governance and Information	Not in coastal areas since 2010.				
LIFE Climate Action	Climate Change Mitigation	Andalusian blue carbon for climate change mitigation: quantification and valorisation mechanisms (*LIFE BLUE NATURA*)	Andalusia	2015-2019	22	2.51 (60%)
	Climate Change Adaptation	Protection of key ecosystem services by adaptive management of climate change endangered Mediterranean socio- ecosystems (*LIFE ADAPTAMED*)	Andalusia	2015-2020	22	5.46 (60%)
	Climate Governance and Information	Sharing awareness and governance of Adaptation to climate change in Spain (*LIFE SHARA*)	Spain Portugal	2016-2021	18	1.57 (60%)

Table C2. Classification of adaptation options categories (MAGRAMA, 2016). (P: protection, A: accommodation, R: retreat; O: others).

Code	Options	Category (1)	Category (2)
1	Risk analysis & Assessment	*Social* Technology/Information	P, A, R
2	Coastal monitoring	*Social* Technology/Information	P, A, R
3	Early warning systems	*Social* Technology/Information/Behaviour	A
4	Beach and dune regeneration	*Structural-Physical* Engineering/NBS	P
5	Beach and dune creation	*Structural-Physical* Engineering	P
6	Wetland restoration & conservation	*Structural-Physical* NBS	P
7	Sediment management	*Structural-Physical* Engineering/NBS	P
8	Coastal protection structures (seawalls, waterfronts)	*Structural-Physical* Engineering	P
9	Coastal stabilization structures (groins, breakwaters)	*Structural-Physical* Engineering	P
10	Infrastructure adaptation	*Structural-Physical* Engineering	A
11	Adaptation code and normative	*Structural-Physical/Institutional* Engineering/Laws & Regulations	A
12	Insurances	*Institutional* Economy	A
13	Structure realignment along the coast	*Structural-Physical/Social* Engineering/Behaviour	R
14	Structure realignment in estuaries and river mouth	*Structural-Physical/Social* Engineering/Behaviour	R
15	Land acquisition	*Social* Behaviour	R
16	Land use changes	*Institutional/Social* Laws & Regulations/ Behaviour	A
17	Promoting wetland migration and creation of new areas	*Physical/Institutional/Social* NBS/ Laws & Regulations/Behaviour	R
18	Training & awareness	*Social* Education/Information	O
19	Reduction of barrier & limits	*Social/Institutional* Information/ Laws & Regulations	O
20	Decision making integration	*Institutional* Laws & Regulations	O
21	Research	*Social* Information	O
22	Assessment of ecosystem services	*Institutional* Economy/Information	O
23	Relocation	*Social* Behaviour	R
24	Concession management	*Institutional* Policy & Administration	A, R
25	Protected areas		O
26	ICZM		All

Table C3. Reclassification of categories of adaptation options (see codes in Table C2).

Type	Code CAS
Soft measures	4, 5, 7
Hard measures	8, 9, 10
NBS	6, 17
Mixed (soft + hard)	4+8, 4+9, 5+8, 7+8
Training + Awareness	1, 2, 3, 18, 19
Integration decision-making process	11, 12, 13, 14, 15, 16, 20, 26
Research	21
Evaluation ecosystem services	22
Protected areas	23, 24, 25
w/o specifying	No code

Table C4. DGSCM objectives and their relation with adaptation actions included in the CAS (see codes in Table C2).

<table>
<tr><th colspan="2">DGSCM objectives</th><th>Code CAS</th></tr>
<tr><td rowspan="3">Coast protection and conservation</td><td>Control coast regression</td><td>2, 4, 5, 7, 8, 9</td></tr>
<tr><td>Protect and recover coastal systems</td><td>6</td></tr>
<tr><td>Improve coastal knowledge</td><td>1, 3, 18, 19, 20, 21, 22</td></tr>
<tr><td colspan="2">Improve and ensure the public and free use of the coast</td><td>Not related</td></tr>
<tr><td colspan="2">Plan, conserve, protect and improve the marine environment</td><td>Not related</td></tr>
<tr><td colspan="2">Ensure and manage the Marine-Terrestrial Public Domain</td><td>10, 11, 12, 13, 14, 15, 16, 17, 23, 24, 25, 26</td></tr>
</table>

Table C5. Expected timing for the acceptable limit for the current strategy at different levels of reduction in PCC (in %) considering the integrated effect of current evolution rates (EV) and SLR in shoreline evolution for Catalonia and tourism brands.

Territorial unit	SLR scenario	10%	15%	20%	25%
Catalonia	RCP4.5 + EV	2025	2030	2035	2040
	RCP8.5 + EV	2025	2030	2035	2040
	H+ + EV	2020	2025	2030	2030
Costa Brava	RCP4.5 + EV	2025	2030	2040	2045
	RCP8.5 + EV	2025	2030	2040	2045
	H+ + EV	2025	2025	2030	2035
Costa de Barcelona	RCP4.5 + EV	2025	2025	2035	2040
	RCP8.5 + EV	2025	2025	2035	2040
	H+ + EV	2025	2025	2030	2030
Barcelona city	RCP4.5 + EV	2025	2030	2035	2040
	RCP8.5 + EV	2025	2030	2035	2040
	H+ + EV	2025	2025	2030	2035
Costa Dorada	RCP4.5 + EV	2020	2025	2030	2035
	RCP8.5 + EV	2020	2025	2030	2035
	H+ + EV	2020	2025	2025	2030

Table C6. Sand volume requirements (in M m^3) for Catalan beaches considering different nourishment criteria and assuming no variation in GDP and PCC.

Nourishment criteria		Year	RCP4.5 + EV	RCP8.5 + EV	H+ + EV
Urban and semi-urban beaches	Compensate to 40 m beach width	2050	36.4	36.4	54.6
		2075	63.5	73.0	130.3
		2100	101.8	123.9	255.1
Urban and semi-urban beaches	Compensate for any loss	2050	51.1	51.1	77.6
		2075	82.1	95.1	162.4
		2100	126.0	152.2	291.1
All beaches	Compensate for any loss	2050	107.5	107.5	144.1
		2075	176.6	194.6	287.3
		2100	263.7	300.0	490.0

Table C7. Sand volume requirements (in M m^3) among tourism brands considering the criteria stablished in this work and assuming no variation in GDP and PCC.

Tourism brand	Year	RCP4.5 + EV	RCP8.5 + EV	H+ + EV
Costa Brava	2050	10.7	10.7	16.5
	2075	18.2	21.2	39.3
	2100	29.2	36.2	81.8
Costa de Barcelona	2050	14.7	14.7	19.3
	2075	25.2	27.7	43.8
	2100	39.1	45.3	80.9
Barcelona city	2050	1.4	1.4	2.2
	2075	2.4	2.8	4.9
	2100	3.8	4.6	9.3
Costa Dorada	2050	9.6	9.6	16.7
	2075	17.6	21.3	42.3
	2100	29.8	37.8	83.1

Table C8. Expected timing of the ATP for beach nourishment for Catalonia considering the integrated effect of current evolution rates (EV) and SLR in shoreline retreat.

Management Strategy	SLR scenario	ATP1	ATP2
		25 M m3	50 M m3
No variation in GDP (no PCC losses)	RCP4.5 + EV	2040	2065
	RCP8.5 + EV	2040	2060
	H+ + EV	2030	2045
2% GDP decline (20% reduction in PCC)	RCP4.5 + EV	2060	2080
	RCP8.5 + EV	2055	2075
	H+ + EV	2040	2055

Table C9. Expected timing for beach nourishment among tourism brands considering a total sediment stock of 50 Mm^3 according to the distribution criteria defined by the competent Administration.

Tourism brand	SLR scenario	Physical criterion	Economic criterion
Costa Brava	RCP4.5 + EV	2065	2080
	RCP8.5 + EV	2060	2075
	H+ + EV	2045	2055
Costa de Barcelona	RCP4.5 + EV	2060	2035
	RCP8.5 + EV	2055	2035
	H+ + EV	2045	2030
Barcelona city	RCP4.5 + EV	2065	>2100
	RCP8.5 + EV	2060	>2100
	H+ + EV	2050	2090
Costa Dorada	RCP4.5 + EV	2065	2060
	RCP8.5 + EV	2060	2055
	H+ + EV	2045	2040

Table C10. Expected timing for users' distribution promoted by new spatial planning policies for Catalonia considering the integrated effect of current evolution rates (EV) and SLR in shoreline retreat.

Management Strategy	SLR scenario	Excluding Ebro Delta beaches	Throughout the entire territory
No variation on GDP (no PCC losses)	RCP4.5 + EV	2050	2055
	RCP8.5 + EV	2050	2055
	H+ + EV	2030	2040
2% GDP decline (20% reduction in PCC)	RCP4.5 + EV	2070	2075
	RCP8.5 + EV	2065	2070
	H+ + EV	2045	2050

Annex D

Scientific contributions

Publications

López-Dóriga, U.; Jiménez, J.A.; Valdemoro, H.I.; Nicholls, R.J., 2019. Impact of sea-level rise on the tourist-carrying capacity of Catalan beaches. Ocean Coast Manag. 170, 40-50. https://doi.org/10.1016/j.ocecoaman.2018.12.028

López-Dóriga, U.; Jiménez, J.A.; Bisaro, A.; Hinkel, J., 2020. Financing and implementation of adaptation measures to climate change along the Spanish coast. Sci. Total Environ. 712, 135685. https://doi.org/10.1016/j.scitotenv.2019.135685

López-Dóriga, U.; Jiménez, J.A., 2020. Relative sea-level rise induced changes in habitat distribution in the Ebro Delta: Implications for adaptation strategies. In N. Hardiman and Institution of Civil Engineers (Eds.), *ICE Coastal Management 2019 Conference: Joining forces to shape our future coasts*, pp. 113-126, eISBN: 978-0-7277-6515-4.

López-Dóriga, U.; Jiménez, J.A. 2020. Impact of Relative Sea-Level Rise on low-lying coastal areas of Catalonia, NW Mediterranean, Spain. Water, 12(11), 3252. https://doi.org/10.3390/w12113252

Conference participation

López-Dóriga, U., Jiménez, J.A., Valdemoro, H.I., 2017. The impact of SLR on the recreational use of Catalan beaches. Application in the Costa Brava. *13th UK Young and Coastal Scientists and Engineers Conference (YCSEC)*, Bath, United Kingdom (oral presentation).

López-Dóriga, U., Villares, M.; Roca, E., 2017. La gestión costera ante los escenarios de cambio climático: un análisis de percepción social. *Conama Local València 2017: Las ciudades conectan naturalmente*, Valencia, Spain (poster presentation).

López-Dóriga, U., Jiménez, J.A.; Bisaro, A.; Hinkel, J., 2019. Adaptation measures to climate change along the Spanish coast. How are we doing? *European Climate Change Conference (ECCA)*, Lisbon, Portugal (poster presentation).

López-Dóriga, U. Jiménez, J.A., 2019. Relative sea-level rise induced changes in habitat distribution in the Ebro Delta: implications for adaptation strategies. *ICE Coastal Management*, La Rochelle, France (oral presentation).

Participation in research projects

PaiRisClima, “El Paisaje del Riesgo Costero en el litoral catalán. La influencia del cambio climático” CGL2014-55387-R

M-CostAdapt, “Rutas de Adaptación al cambio climático en la zona costera mediterránea. Superando los límites de la adaptabilidad” CTM2017-83655-C2-1-R

International internships

School of Civil Engineering and the Environment. University of Southampton, United Kingdom.

Period: From April 3rd to July 7th, 2017.

Host researcher: Professor Robert Nicholls.

Objective: to develop adaptation measures for Catalan beaches with especial emphasis on the tourism sector.

Global Climate Forum, Berlin, Germany.

Period: From October 1st to December 20th, 2018.

Host researchers: Dr. Jochen Hinkel and Dr. Alexander Bisaro.

Objective: to assess adaptation measures implemented along the Spanish coastline and diagnosis of the current situation regarding the adaptability of the coastal zone to climate change.

Obtained grants

2015. Ayudas para contratos predoctorales para la formación de doctores FPI2015. MINECO. Referencia de la ayuda: BES-2015-073197. 2016-2019 (4 years)

2017. Beques d'investigació de l'Obra Social de La Caixa-UPC per a Mobilitat Internacional.