Universidade de Aveiro
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LUIZ NORBERTO LACERDA MAGALHÃES FILHO

AVALIAÇÃO DOS IMPACTOS DA ELEVAÇÃO DO NÍVEL DO MAR NO VALOR DOS SERVIÇOS ECOSSISTÊMICOS NA ZONA COSTEIRA DO ATLÂNTICO

EVALUATING THE IMPACTS OF SEA LEVEL RISE ON COASTAL ECOSYSTEM SERVICES VALUES ALONG THE ATLANTIC COASTAL ZONE

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Tese apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Ciências e Engenharia do Ambiente, realizada sob a orientação científica do Doutor Peter Cornelis Roebeling, Investigador Auxiliar do Departamento de Ambiente e Ordenamento da Universidade de Aveiro, do Doutor Luis Costa, Investigador do Departamento de Resiliência Climática do Instituto Potsdam de Pesquisas sobre o Impacto Climático, e do Doutor Waldecy Rodrigues, Professor do Departamento de Economia da Universidade Federal do Tocantins.

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Dedico este trabalho a minha família e amigos.

o júri

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palavras-Chave

Costa Atlântica; Cenários de Mudanças Climáticas; Cenários Socioeconómicos; Aumento do Nível do Mar, Processo de Inundação; Mudanças de Uso do Solo; Valor do Serviço Ecossistêmico; Transferência de Benefícios.

Resumo

Os ecossistemas costeiros são diversos, altamente produtivos, ecologicamente importantes em escala global, e altamente valiosos pela ampla gama de serviços que prestam aos seres humanos. No entanto, o valor dos serviços ecossistemas costeiros são vulneráveis ao aumento do nível do mar. O objetivo do presente estudo é determinar o valor dos serviços ecossistêmicos na zona costeira Atlântica, através de uma transferência de função meta-analítica, analisando o uso da terra e as mudanças socioeconômicas ao longo dos anos, e os valores em risco devido a futuras mudanças no clima, nível do mar e condições socioeconómicas. Inicialmente, avaliou-se a influência de fatores locais na erosão costeira, através dos fatores antropogênicos e naturais que estão relacionados ao recuo do litoral, adotando-se análises estatísticas, correlação e regressão. Em seguida, uma meta-análise global é realizada para estimar as funções do valor dos serviços ecossistêmicos locais (para os serviços: Provisão, Regulação & Manutenção; Cultural) em 12 biomas (Sistema Costeiro, Zona húmida costeira, Recife de Coral, Área Cultivada, Deserto, Pradaria, Zona húmida Interior, Oceano, Floresta Temperada ou Boreal, Floresta Tropical, Água Doce e Bosque). A confiabilidade dessas funções é testada e foi demonstrado que a transferência de função meta-analítica tem um desempenho melhor do que a transferência de valor unitário e, em adição, que a transferência de função meta-analítica local (ou seja, com base em valores de variáveis explicativas locais) fornece estimativas mais confiáveis do que a transferência de função meta-analítica global (ou seja, com base nos valores médios das variáveis explicativas globais). Por sua vez, essas funções de valor dos serviços ecossistêmicos foram aplicadas a países pertencentes à zona costeira Atlântica, para mapear e avaliar os valores fornecidos pelos serviços ecossistêmicos na zona costeira Atlântica no período 2005-2015. Os resultados mostraram que os serviços culturais (50% do total), o bioma Floresta Tropical (33% do total) e o continente da América Latina e Caribe (55% do total) representam os maiores valores de serviços ecossistêmicos ao longo da zona costeira do Atlântico. Apesar da diminuição das áreas naturais, principalmente devido ao aumento das áreas urbanas ao longo da zona costeira Atlântica, houve um aumento dos valores dos serviços ecossistêmicos ao longo do tempo (+21%), devido ao aumento da renda (+13%) e da população (+15%) no período 2005-2015. Finalmente, foi explorado o impacto conjunto das inundações e do desenvolvimento socioeconômico nos futuros serviços e valores ecossistêmicos na zona costeira do Atlântico até 2100. Para este fim, mapas de probabilidade de inundação e estimativas de valores de serviços ecossistêmicos locais são derivados para combinações de cenários de "*Representative Concentration Pathway*" (RCP 4.5 e 8.5) e *"Socioeconomic Pathway"* (SSP 1 a 5) para obter valores futuros de serviços ecossistêmicos costeiros. O maior valor dos serviços ecossistêmicos em risco está relacionado à ocorrência do RCP 8.5 em combinação com SSP5 (ou seja, os cenários pessimistas com uma narrativa relacionada ao desenvolvimento de combustíveis fósseis) – até 2100, a zona costeira com as maiores perdas prováveis em valor dos serviços ecossistêmicos de Provisão é a Europa (~5,9 € bilhões/ano), para Regulação & Manutenção é a América do Norte (~6,0 € bilhões/ano) e para Cultural é América do Sul (~21,3 € bilhões/ano). Embora o crescimento da população e da renda resulte em um aumento no valor dos servicos ecossistêmicos, há também aumento dos valores em risco. Essas tendências nos valores dos serviços ecossistêmicos ao longo dos anos merecem atenção cuidadosa por parte dos formuladores de políticas. Uma diminuição na oferta de serviços (devido à conversão do uso da terra) e o aumento na demanda por serviços ecossistêmicos (devido ao crescimento da renda e da população) podem, potencialmente, levar ao colapso desses serviços ao longo do tempo.

Keywords

Atlantic Coastal Zone; Climate Change Scenarios; Socio-Economic Scenarios; Sea Level Rise; Flood Process; Land Use Change; Ecosystem Service Value; Benefit Transfer.

Abstract

Coastal ecosystems are diverse, highly productive, ecologically important at the global scale, and highly valuable for the wide range of services they supply to human beings. Coastal ecosystem services and values are, however, vulnerable to sea-level rise. The objective of the present study is to determine the value of ecosystem services in the Atlantic coastal zone, through meta-analytic function transfer, analyzing land use and socio-economic changes over the years, and the values at risk due to future changes in climate, sea level and socio-economic conditions. Initially, it was evaluated the influence of local factors on coastal erosion, through the anthropogenic and natural factors that are related to the retreat of the coastline, by adopting statistical correlation and regression analyses. Next, a global meta-analysis is performed to estimate local ecosystem service value functions (for Provisioning, Regulating & maintenance, and Cultural ecosystem services) across 12 biomes (Coastal System, Coastal Wetland, Coral Reef, Cultivated Area, Desert, Grassland, Inland Wetland, Marine, Temperate or Boreal Forest, Tropical Forest, Fresh Water and Woodland). The reliability of these functions is tested, and it was shown that meta-analytic function transfer performs better than unit value transfer and, in addition, that local meta-analytical function transfer (i.e., based on local explanatory variable values) provides more reliable estimates than global meta-analytical function transfer (i.e., based on mean global explanatory variable values). In turn, these ecosystem service value functions were applied to countries that belong to the Atlantic coastal zone, to map and assess the values provided by ecosystem services on the Atlantic coastal zone over the period 2005-2015. Results showed that Cultural services (50 % of total), Tropical Forest biome (33 % of total) and Latin America & Caribbean continent (55% of total) represent largest ecosystem service values along the Atlantic coastal zone. Despite the decrease in natural areas, mainly due to the increase in urban areas along the Atlantic coastal zone, there was an increase in ecosystem service values over time (+21%), due to an increase in income (+13%) and population (+15%) over the period 2005-2015. Finally, the joint impact of flooding and socio-economic development on future ecosystem services and values in the Atlantic coastal zone by 2100 were explored. To this end, flood probability maps and local ecosystem service value estimates are derived for combinations of Representative Concentration Pathway (RCP 4.5 and 8.5) and Shared Socioeconomic Pathway (SSP 1 to 5) scenarios to obtain future values of coastal ecosystem services. The greatest value of ecosystem services at risk is related to the occurrence of RCP 8.5 in combination with SSP5 (i.e., the worst-case scenarios with a narrative related to fossil-fueled development) – by 2100, the coastal zone with the highest probable losses in Provisioning ESV is Europe (~5.9 € billion/year), for Regulating & maintenance ESV this is North America (~6.0 € billion/year) and for Cultural ESV this is South America (~21.3 € billion/year). Although population and income growth result in an increase in ESV, it also emphasizes the ecosystem service values at risk. These trends in ecosystem service values over the years deserves careful attention by policy makers. A decrease in the supply of services (due to land use conversion) and the increase in demand for ecosystem services (due to income and population growth) could, potentially, lead to the collapse of these services over time.

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LIST OF ABBREVIATIONS

Afric	African continent
APer	Agricultural land by percentage of land area
Asia	Asian continent
BT	Benefit Transfer
CCI	Climate Change Initiative
CMIP5	5th Climate Model Intercomparison Project
CMIP6	6th Climate Model Intercomparison Project
CoRf	Coral Reef biome
CSys	Coastal System biome
CuAr	Cultivated Area biome
CWet	Coastal Wetland biome
Dred	Annual dredging
Dser	Desert/Snow biome
ES	Ecosystem Service
ESA	European Space Agency
ESV	Ecosystem Service Value
ESVD	Ecosystem Service Value Database
Euro	European continent
FAO	Food and Agriculture Organization
FPer	Forest area by percentage of land area
Fprot	Fully protected area
FrWa	Fresh Water biome
GEE	Google Earth Engine
GIS	Geographic Information System
GNI	Gross National Income
Gras	Grassland biome
Groin	Total length of groins built
IIASA	International Institute for Applied Systems Analysis
InWt	Inland Wetland biome
IPCC	Intergovernmental Panel on Climate Change
LaAm	Latin American continent
MA	Meta-Analysis
Mari	Marine biome
MProt	Percentage of Marine Protected areas
NoAm	North American continent
Nprot	Not protected area
NSUT	Non-Structural Utility Theoretic
Ocea	Oceanic continent
PDen	Population Density
Pprot	Partially protected area
Precp	Precipitation
RCP	Representative Concentration Pathway
RY	Reference Year
SLR	Sea Level Rise
SSP	Shared Socioeconomic Pathway
SSUT	Strong Structural Utility Theoretic
TE	Transfer Error
TeFo	Temperate/Boreal Forest biome
TProt	Percentage of Terrestrial Protected areas
TrFo	Tropical Forest biome
UrbA	Urban Area
uBTM	Uncertainty Bathtub Model
Wood	Woodland biome
WSUT	Weak Structural Utility Theoretic
WTP	Willingness-to-pay

CHAPTER 1

1. Introduction

1.1. Motivation

The Earth Planet is a coastal planet, comprises 361.1 million km² of water (71% of total planet surface) and 148.9 million km² of land area (29% of total planet surface). They both interact intensively and extensively along the world's coastline (Burke et al., 2001). Almost 85% of the countries of the world have a coastline either with the open oceans, inland seas, or both (Martínez et al., 2007).

The coasts' vast extent and distribution results in an ample variety of geomorphological features, weather regimes and biomes. All these different characteristics result in an equally large variety of biomes found along the coasts. On the terrestrial part there are different kinds of forests (tropical, temperate, and boreal), shrubs, and savannas, while aquatic ecosystems comprise mangroves, salt marshes, estuaries, coral reefs, sea grasses and the coastal shelf (e.g. Martinez et al., 2007; Van der Maarel, 1993; Burke et al., 2001).

Coastal zones are among the most important regions for humanity. More than 30% of the world population live in coastal communities – which are twice as densely populated as inland areas (MEA, 2003; Barbier et. al., 2008; Rao et al., 2015) – and nearly 2.4 billion people (about 40% of the world population) live within 100 km (60 miles) of the coast (Burke et al., 2001). Out of the 33 world megacities, 21 are found on the coast (Martinez et al., 2007) and their resident population directly benefits from as well as impacts on the environment and coastal ecosystems. There are numerous interactions between coastal communities and natural ecosystems, and it is increasingly recognized that natural ecosystems play a crucial role in determining human wellbeing (TEEB, 2010).

Estimates suggest that over 75% of the global Ecosystem Services Value (ESV) is generated by coastal ecosystems (Costanza et al., 1997). Hence, the economic value of goods and services provided by coastal ecosystems is crucial for many countries' economies. Ecosystem services (ES) include provisioning services (such as supply of food via fishery production, fuel wood, energy resources, and natural products), regulation & maintenance services (such as shoreline, nutrient regulation, carbon sequestration, detoxification of polluted waters, and waste disposal), and cultural services (such as tourism, spiritual and recreation) (MA, 2005). Coastal ecosystem services values are, however, vulnerable to impacts from climate change, sea level rise, erosion, storm events, population growth and economic development.

Sea Level Rise (SLR) is a process associated with the thermal expansion of ocean waters and melting of land-based ice. This process is a common problem that affects about 70% of coastal zones worldwide (Feagin et al., 2005). The total global mean sea-level rose by 0.16 m between 1902 and 2015. However, in the period 2006–2015, the global SLR rate was 3.6 mm yr^{-1}, about 2.5 times higher than in the period 1901–1990, 1.4 mm yr^{-1} (The IMBIE Team, 2018). The melting of ice sheets and glaciers were the most important sources of sea-level rise over the period of 2006–2015, 1.8 mm yr^{-1}, exceeding the influence of the thermal expansion of ocean water, 1.4 mm yr^{-1} (Slater et al., 2020). What makes this problem even more worrying is that, according to the Intergovernmental Panel on Climate Change (IPCC) through its climate change scenarios, it is expected to increase – such that this process is often seen as one of the major threats to coastal ecosystems. (NOAA, 2021). This situation could have very substantial impacts on river deltas and, without any adaptation, may wipe-out entire islands (McLean et al., 2001) turning some of them as well as low-lying areas unviable by 2100 (Nicholls et al., 2007).

Prominent examples of climate change scenarios include scenarios by the IPCC. The most recent, in IPCC 5th and 6th Climate Model Intercomparison Project (CMIP5 and CMIP6), includes a set of scenarios called Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs), respectively, they are a larger set of scenarios in the literature represented in different RCPs and SSPs (Riahi et al., 2017; Taylor et al., 2012). Just to get an idea, the rate of global mean sea-level rise is projected to reach 4 mm yr^{-1} under a RCP 2.6, very stringent emission scenario, and 15 mm yr^{-1} under RCP 8.5, worst-case scenario, in 2100 (IPCC, 2019).

To better understand the SLR phenomenon from an economic point of view, the socio-economic impacts of sea-level rise have been classified as follows (Klein & Nicholls, 1999): (1) direct loss of economic, ecological, cultural and subsistence values through loss of land, infrastructure and coastal habitats; (2) increased flood risk of people, land and infrastructure, together with the aforementioned values; and (3) other effects related to changes in water management, salinity and biological activities. Taking this into account, climate change scenarios are a powerful tool for understanding the impacts, charting response strategies, and supporting climate policy making. Through them, it is possible to define the vulnerabilities of countries to the consequences of climate change and accelerated SLR.

Increasingly, coastal ecosystem services and values studies have been published over the last decades. Martinez et al. (2007) explored the economic value provided by ecosystems services for the world coast (for the year 2003), using unit value transfer based on values from Costanza et al. (1997). Roebeling et al. (2013), who studied past (1975) to future (2050) land cover and ES value losses from coastal erosion along the European coast, using climate change scenario (SRES B1 and A1F) simulations from the Dynamic and Interactive Vulnerability Assessment (DIVA) tool to explore future coastal erosion projections (Hinkel & Klein, 2009) in combination with unit value transfer based, also, on values from Costanza et al. (1997). Lately, Paprotny et al. (2021) studied the ES value losses that could occur due to SLR-induced coastal erosion for the years 2050 and 2100, adopting coastal erosion projections from Vousdoukas et al. (2020) under two future emission scenarios (RCP 4.5 and RCP 8.5), while also using unit value transfer based on, updated, values from de Groot et al. (2012) and Costanza et al. (2014). Although studies have accounted for the temporal evolution of the coast, coastal erosion and ecosystem service value losses based on updated unit ecosystem service values; they assumed socioeconomic conditions to remain unchanged (over time) and continue to be based on unit value transfer (i.e. values are not adjusted to local conditions).

1.2. Objectives and approach

The foregoing constitutes the background and motivation for this thesis. Namely, the overall objective of the present study is to determine the value of coastal ecosystem services in the face of global change (such as climate change, population growth and economic development), through meta-analytic function transfer, analyzing land use and socio-economic changes over the years (2005-2015), and assessing the values at risk due to future changes in climate, sea level and socio-economic conditions (by 2100). A case study is provided for countries on the Atlantic Coastal zone. Specific objectives and associated methods are:

1. Assess the key anthropogenic and natural factors that influence the rate of coastline retreat. Based on historical data over the period 1980 to 2001, correlation and regression analyses was used to assess the relationship between coastline retreat (dependent variable) and anthropogenic and natural factors (dredging volume; groin lengths; storm events).

2. Estimate meta-analytic value functions for Provisioning, Regulating & maintenance and Cultural ecosystem services across 12 biomes. Based on primary value estimates (from the Ecosystem Service Valuation Database) and complementary explanatory variables (from the World Bank Data and FAOSTAT), a meta-analysis was performed for 3 ecosystem services (Provisioning; Regulating & maintenance; Cultural) provided by 12 main land covers (Coastal systems; Coastal wetlands; Coral reefs; Cultivated areas; Desert; Fresh water; Grasslands; Inland wetlands; Open Ocean; Temperate/Boreal forests; Tropical forests; Woodlands).

3. Map and assess the values provided by Provisioning, Regulating & maintenance and Cultural ecosystem services in the Atlantic coastal zone over the period 2005–2015. Meta-analytic ecosystem service value functions were applied to a 100 km coastal zone of countries on the Atlantic coastal zone, using land use and socio-economic data for 2005, 2010 and 2015.

4. Analyze the joint impact of flooding and socioeconomic development on the future ecosystem services and values in the Atlantic coastal zone by 2100. Flood probability maps (using Uncertainty Bathtub Model) and local ecosystem service value estimates (using meta-analytic value function transfer) are derived for a combination of Representative Concentration Pathway (RCP) and Shared Socioeconomic Pathways (SSP) scenarios.

1.3. Advance beyond state of knowledge

Ecosystem service values were designed to provide access to values in monetary units for ecosystem services, to help recognize the importance of the services provided, and thereby assist in the development of environmental policies. In this thesis, we estimated and used meta-analytic ecosystem service value functions - thus considering the local context of the country and area under analysis. Meta-analytic function transfer, generally, reduces value transfer errors as it takes into account local specifications to determine ESV's. Through the application of meta-analytic ecosystem service value functions it is possible to estimate values for 3 different types of ecosystem services (Provisioning; Regulating & maintenance; Cultural) and 12 different types of land covers (Coastal systems; Coastal wetlands; Coral reefs; Cultivated areas; Desert; Fresh water; Grasslands;

Inland wetlands; Open ocean; Temperate/Boreal forests; Tropical forests; Woodlands) in the world.

Furthermore, we map and assess the historical evolution of ecosystem service values for a coastal zone of 100 km of all the 63 countries that, together, form the Atlantic coastal zone, over the period 2005-2015. To this end, meta-analytic ecosystem service value functions for a wide range of coastal biomes and ES value types are used and applied to countries on the Atlantic coastal zone, using land use and socio-economic data for 2005, 2010 and 2015.

This study also analyzed the future evolution of ecosystem service values in the Atlantic coastal zone, in the face of climate change, sea-level rise and socio-economic development. The integration of methodologies with the Uncertainty Bathtub Model (uBTM; for the creation of alternative flood probability maps), ecosystem services valuation (using meta-analytic value functions), and RCP climate and SSP socioeconomic scenarios (for 2100). This study goes beyond previous studies by using meta-analytic value function transfer (rather than unit value transfer), combinations of climate change and socioeconomic scenarios (rather than climate change scenarios only) and, finally, applying the analysis to 5 continents (rather than Europe only).

Finally, results are discussed and reflected upon, and the relevance for coastal management and policy makers is emphasized. Namely regarding the notion that nature and ecosystems contribute to human well-being, the conscience that ecosystem services and values are not equally distributed and change over time, and the importance of integrating natural capital, ecosystem services and values in decision making.

1.4.Thesis outline

The remainder of this thesis is structured as follows. **Chapter 2** evaluates the influence of local factors on coastal erosion, for the case of Vagueira beach in Portugal, The anthropogenic and natural factors that are related with the retreat of the coastline are assessed using a statistical correlation and regression analyses. **Chapter 3** presents the meta-analysis conception of three meta-regression ecosystem service value functions (for Provisioning, Regulating & maintenance and Cultural ecosystem services). These models are applied determining values for 12 different biomes. Validity and reliability are assessed through transfer error analysis. **Chapter 4** assesses and maps the values provided by these three ecosystem services in countries that belong to the Atlantic coastal zone, using meta-analytic function transfer in combination with land use and socio-economic information for the years 2005, 2010 and 2015. **Chapter 5** analyzes the effects of climate, sea-level and socio-economic changes on the future ecosystem service values in Atlantic coastal zone by 2100, through the construction of flood probability maps (using the Uncertainty Bathtub Model) combined with local ecosystem service value estimates (using meta-analytic function transfer) and scenario analysis. Finally, **Chapter 6** concludes with an overview of the research main results and their policy implications.

CHAPTER 2

2. INFLUENCE OF LOCAL FACTORS ON COASTAL EROSION: THE CASE OF VAGUEIRA BEACH IN PORTUGAL*

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ABSTRACT

Vagueira Beach, on the central Portuguese coast, is known as one of the places in Europe most af-fected by coastal erosion. The area has suffered more than 156 m of coastline retreat from the period 1958 to 2001. With the aim of evaluating the influence of local factors on coastal erosion, this paper assesses the anthropogenic and natural factors that are related to the retreat of the coastline by adopting statistical correlation and regression analyses. Through Pearson's correlation coefficient (r), it was observed that local factors, such as annual dredging at the Aveiro Port entrance ($r = 0.93$), the total length of groins in the Espinho–Vagueira section ($r = 0.89$), and storm events ($r = 0.52$), are directly related to coastline retreat in the area. A multiple linear regression model was developed in which coastline retreat is explained by these same factors over the period 1980–2006. With a coef-ficient determination of $R^2 = 0.91$, it was observed that the length of groins (significant at the 1% level), the dredging of the port entrance (significant at the 5% level), and precipitation (as a proxy for storm events; significant at the 10% level) are significantly correlated with coastline retreat. Hence, it is shown that anthropogenic factors are the main drivers of coastline retreat in Vagueira Beach. This study provides an innovative approach for the assessment of coastal erosion, resulting in important information that could be used for decision-making related to coastal zone manage-ment as it allows us to understand in greater detail the main drivers of coastal erosion.

2.1. Introduction

Coastal areas are among the most critical regions for humanity. Indeed, more than 30% of the world’s population lives in the coastal zone—which is twice as densely populated as inland areas (Alcamo et al., 2003; Barbier et al., 2008; Rao et al., 2015) – with the majority of the total population of more than half of coastal countries living within 100 km from the coastline (Burke et al., 2001). Coastal zones host the majority of centers of political decision, economic and technical cooperation, as well as a large part of the industries and economic activities in many countries (Martinez, et al., 2007). Hence, the increase in coastal erosion directly threatens the majority of the world’s population and economy (Borges et al, 2022; EU, 2022).

The coastal zone is one of the most dynamic environments on the planet and coastline position constantly changes at various times and spatial scales (Borges et al, 2022). The position of the coastline is affected by many factors, some due to natural causes (related to coastal dynamics, climate, and climate change) and others due to human interventions (such as urbanization, dredging, and infrastructure) (EU, 2022; Roebeling et al., 2011; Coelho et al., 2009, Nicholls et al., 2007). As a result of the interaction between these factors, the coastline can move out to sea, stay in place, or be pushed-back toward the continent (Roebeling et al., 2011a; Roebeling et al., 2011b; Roebeling et al., 2013). This indentation, in turn, causes loss of territory and is considered as a process of coastal erosion.

Portugal is located on the Iberian Peninsula in southwest Europe, facing the Atlantic coast. The Portuguese coast is a highly energetic region, suffering from storms generated in the North Atlantic (Cruz, 2008). Central Portugal is one of Europe's coastal areas that suffers most from the processes of coastal erosion (EU, 2022), due to the reduction in the delivery of sediments to the coast, rising sea levels, the in-crease in the frequency of storms, and changes in human settlements (Dias et al., 1994; Alves et al., 2009; Roebeling et al., 2011). Several studies have shown that the Espinho-Mira section is one of the area most vulnerable to coastal erosion (Dias et al., 1994; CEHIDRO/INAG, 1998; Coelho, 2005; Gomes et al., 2006; Barbosa et al., 2006; Coelho et al., 2007; Pereira & Coelho, 2013). This area has a variety of beaches, including Vagueira Beach—a small Portuguese vil-lage situated in the district of Aveiro that annually receives a large inflow of tourists.

Vagueira Beach has suffered about 160 m of coastline retreat over the period 1948–2001 (EU, 2022).

With the purpose of understanding what is aggravating coastal erosion in Central Portugal, the objective of this study is to assess the key anthropogenic and natural factors that influence the rate of coastline retreat. To this end, correlation and regression analyses are performed, relating coastline retreat to anthropogenic and natural factors. This study contributes to previous studies, which have mostly used monitoring and modeling approaches to assess the causes and impacts of coastal erosion (Dias et al., 1994; Coelho et al., 2007; Pereira & Coelho, 2013; Maia et al., 2015; Lira et al., 2016; Pinto et al., 2020), that mostly used monitoring and modeling approaches to assess the causes and impacts of coastal erosion. Hence, this study developed a correlation and regression analysis to assess the key anthropogenic and natural factors that influence the rate of coastline retreat and, thus, could contribute to the development of coastal erosion adaptation strategies in Central Portugal.

The remainder of this paper is structured as follows. Section 2.2 (Materials and methods) provides the definition and sources of data, a characterization of the study area and a description of statistical analyses performed. In Section 2.3 (Results and discussion) results from the correlation and regression analyses are presented, and the influence of the various anthropogenic and natural factors on coastline retreat are discussed. Finally, concluding remarks and observations are provided in Section 2.4.

2.2. Materials and Methods

2.2.1. Characterization of the study area

Vagueira Beach is located on the central Portuguese coast, between Costa Nova and Areão Beaches (see Figure 2.1). This region is influenced by strong urbanization pressure, widespread sedimentary deficit, and frequent wave action and inundation due to energetic storm events (Barbosa et al., 2006). This coastal stretch, marked by the presence of extensive and fragile dunes, sandy beaches of low elevation, and developments parallel to the Ria de Aveiro lagoon, is considered one of the most dynamic types of coasts (Pereira & Coelho, 2013; Lira et al., 2016).

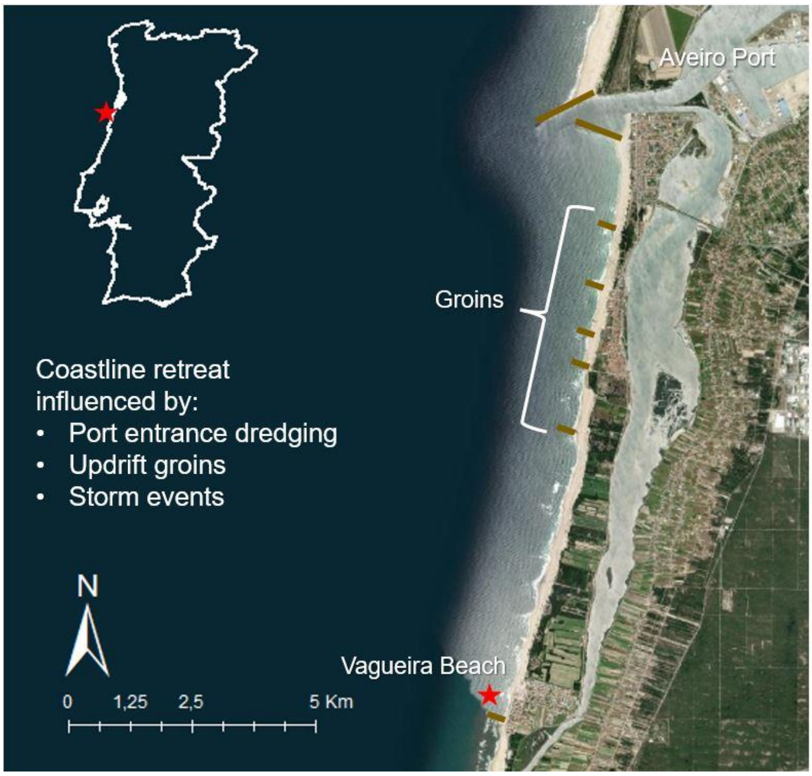

Figure 2.1 - Vagueira Beach study area location in the Ria de Aveiro region (adapted from: Coelho et al., 2007).

Vagueira Beach shows an increase in coastal erosion – with rates of coastline retreat increasing from 1.6 m/year during the late 1950s to 7.1 m/year over the period 1996-2001 (see Table 2.1). Note that rates of coastal erosion are grouped into 4 different periods of time due to scarcity of specific information and, thus, coastline retreat data is based on the best available information.

Table 2.1 - Average rates of the coastline retreat in Vagueira Beach over the period 1958 to 2001 (EU, 2022).

Period (years)	Coastline retreat Annual (m/year)	Total (m)
1958-1969 (12 years)	1.6	19.2
1970-1979 (10 years)	2.4	24.0
19801990 (11 years)	3.9	42.9
1991-1995 (5 years)	5.5	27.5
1996-2001 (6 years)	7.1	42.6
Total	-	156,2

In case the sediment available for coastal drift is equal to the potential sediment transport capacity, the coastline would be in equilibrium and the sediment transport along this coastal stretch would forward the sediments downdrift (Pereira & Coelho, 2013). The morphology of the sector is mainly defined by wave actions that are responsible for the sediment transport that occurs on the littoral. The central Portuguese coast is exposed to very energetic wave climates, which promote a north-to-south directed net littoral drift, estimated to be around 1.1 × 106 m^3/year (Santos et al., 2022). In the past, the Douro River would be able to practically alone provide the amount of sediment needed to balance sediment losses (Coelho et al., 2009b). However, with the construction of dams (between 1972 and 1985), this supply of sediment decreased dramatically (Coelho et al., 2009b, Pombo et al., 2022).

Another factor related to coastline retreat is the dredging that occurs at the Aveiro Port entrance, in which part of this material was, in the past, commercialized for other uses (such as construction and industrial use)—further reducing sediment supply from the north and, thus, accentuating the coastline retreat of the Vagueira Beach (Pereira & Coelho, 2013). Only after 2000 were dredging operations performed for navigation purposes at Aveiro port use in beach and landfill nourishment (when the sediments present the required quality), with only a part deposited at sea, to the south of the breakwater, in an attempt to mitigate coastal erosion.

Anthropogenic interventions and impacts can be even more severe due to the destruction of natural coastal defense structures, in particular the beach and the frontal dune system, which act as the first natural barriers to wave action. Beach tourism, the advance of urbanization, and the construction of industrial areas are the main activities that have resulted in the creation of wind runners, changes in the floodplain, and the extraction of sediments (Komar, 1998). The rate of urbanization in the Ria de Aveiro region increased from 5% in 1975 to 12% in 2006 (Coelho et al., 2009a). This occupation of the coastal area led to the destruction of dunes that provided large volumes of sand for the dynamic inter-action with and natural defense against the sea (Coelho et al., 2009b).

Due to the increase in coastal erosion, the vulnerability of human settlements to losses and damages has increased. This has resulted in the construction of heavy engineering structures (groins, rocky revetments, dikes, and breakwaters) to protect these settlements against the sea. The main structures found along the central Portuguese coast are groins.

Groins are short structures placed perpendicular to the coastline and extended to the surf zone, usually built in straight portions of the shoreline. Their main purpose is to retain sand and promote updrift accretion (Bush et al., 2001). Groins do not add sediment to the coastal system, and secondary negative effects of these structures may anticipate sediment deficit downdrift (see Figure 2.2). At Vagueira Beach, the main negative impacts are registered due to the northern structures, and this is explained by a predominance of currents from the northwest along the considered coastal stretch (Pedrosa, 2013). In addition, the construction of the breakwater at the Aveiro Port entrance in 1942 resulted in the trapping of sediments from the northern part of the considered coastal stretch (APDL, 2022).

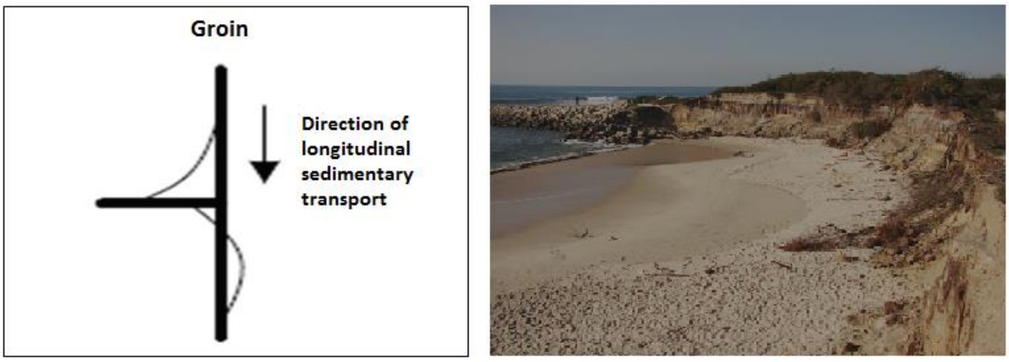

Figure 2.2 - Scheme of the consequences resulting from the construction of groins on the coast and effects of erosion immediately south of the groin in Cortegaça Beach (Pedrosa, 2013).

The number of groins built between Esmoriz Beach and Vagueira Beach increased from none in 1970 to nine in 2006. In 2006 there are nine groins of various lengths (between 100 and 200 meters, each) in this section – totaling 1460 meters of groins (Figure 2.3). Built with the objective of protecting the areas north of where they are located, they tend to further aggravate the coastline retreat in Vagueira Beach. Note that groin sand retention, accretion updrift, and, in particular, sand depletion and erosion downdrift takes several decades before a stable situation is attained (Bush et al., 2001), and hence, the impacts of groins are observed until decades after their construction.

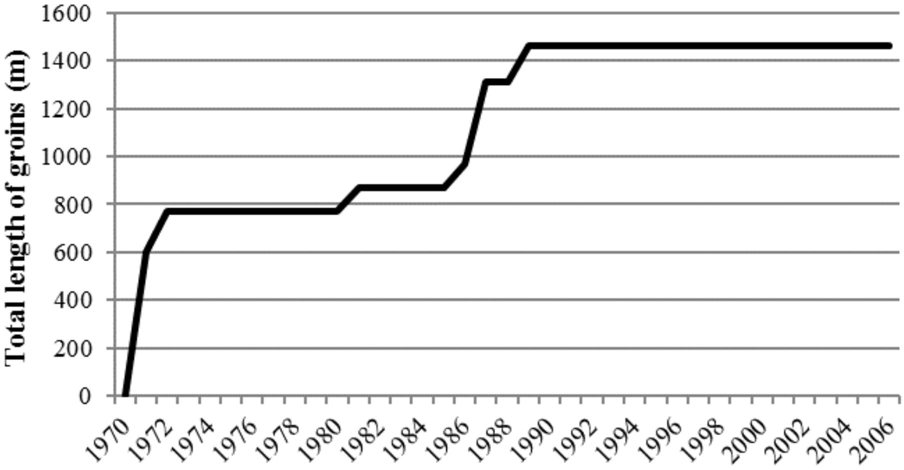

Figure 2.3 - Total length of groins built in the Espinho-Vagueira section over the period 1970 to 2006 (EU, 2022).

Storm events contribute to coastline retreat, changing the beach morphology, in-cluding responses to the direct action of waves, winds, tides, and surges, as well as seasonal changes in the surf zone between storms and calm periods (Costa et al., 2001). Storms generated in the North Atlantic are frequent in winter and can persist for up to 5 days, with significant wave heights as high as 8 m (Costa et al., 2001). However, wave records during storm events are unreliable (incomplete), as during these events, measuring equipment frequently fails due to the high wave energy. A proxy for storm events is precipitation, as periods of intense rainfall (mainly during autumn and winter) are generally ac-companied by storm events (Figure 2.4; see also Section 2.3.1). Over the period 1980–2010, the median annual precipitation was about 950 mm, with a standard deviation in an-nual precipitation of about 175 mm.

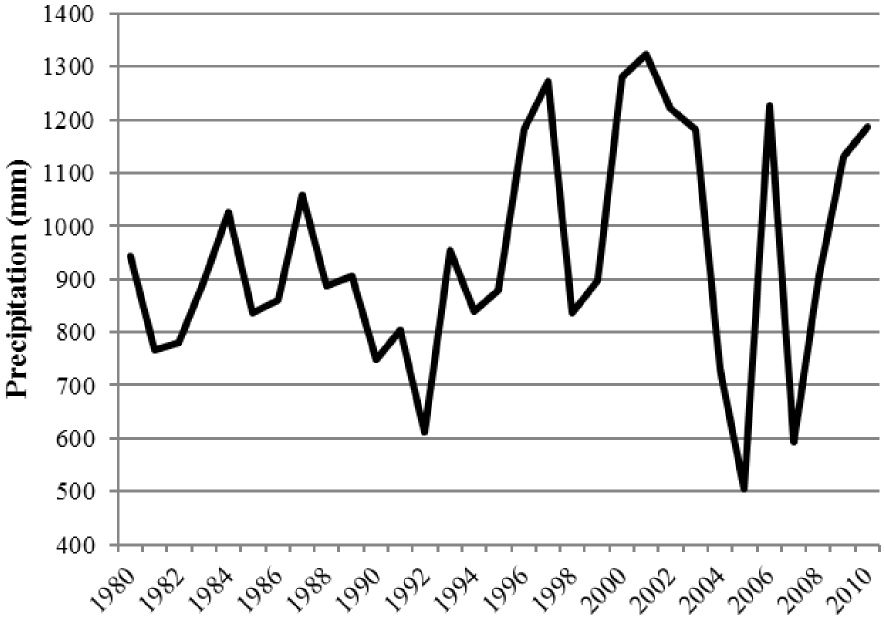

Figure 2.4 - Annual precipitation in Aveiro district over the period 1981 to 2011 (based on: IPMA, 2022).

2.2.2. Data collection

To allow for the assessment of the key anthropogenic and natural factors that ex-plain the rate of coastline retreat, corresponding time series data were collected from government bodies and publications for the Espinho–Mira case study area. t=This analysis adopted data over the period of 1980–2001 (21 years), for which information on all considered variables were available. In particular:

a) Annual coastline retreat (in meters/year) in Vagueira Beach for the period 1980 to 2006 (obtained from the EUROSION project) (EU, 2022);

b) Annual dredging (in m3/year) at the Aveiro Port entrance for the period 1980 to 2010 (data provided by the Port of Aveiro);

c) Total length of groins built (in meters) in the Espinho-Vagueira section for the period 1980 to 2001 (obtained from the EUROSION project) (EU, 2022);

d) Annual precipitation (in mm/year) in the Aveiro district for the period 1980 to 2010 (obtained from the Instituto Português do Mar e da Atmosfera) (IPMA, 2022).

2.2.3. Statistical analysis

In seeking to determine which anthropogenic and natural factors influence coastal erosion in Vagueira Beach, a series of correlation and regression analyses were performed with the statistical software SPSS (Statistical Package for Social Science; version 15.0).

Correlation analysis was applied to assess the correlation between these independent variables and coastline retreat (dependent variable). The coefficient of correlation (r) is a measure of the degree of linear relationship between two quantitative variables (where -1 indicates there is a perfect negative linear relationship, 0 indicates that there is no linear relationship, and +1 indicates a perfect positive linear relationship). The closer the correlation coefficient is to -1 or +1, the stronger is the linear association between the two variables (Rummel, 2022; Larson & Farber, 2018). The Pearson's correlation coefficient (r) is given by:

$$r = \frac{\sum(x_i - x) \times (y_i - y)}{\sqrt{(\sum(x_{i-\bar{x}})^2) \times (\sum(y_{i-\bar{y}})^2)}} \tag{1}$$

where r is the Pearson correlation coefficient of a group of variables x with another group of variables y.

In turn, a multiple linear regression analysis was performed. The dependent variable is annual coastline retreat, and the independent variables are annual dredging, total length of groins and annual precipitation. The goal of multiple linear regression analysis is to find a regression equation that provides a better perception of the sign and the extent to which independent variables determine values of the dependent variable – thus, aiming to find regression coefficients β that best fit the dependent variable y (Hair et al., 2009):

$$y = \beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n + \varepsilon \tag{2}$$

where y is the dependent variable, x are the independent variables, □ are the regression coefficients, and where ε is the residue error of prediction. The latter is the difference between the actual values and those predicted by the regression model and is assumed normally distributed with zero mean and constant variance (σ^2) (Hair et al., 2009; Larson & Farber, 2018).

In seeking to determine the extent to which anthropogenic and natural factors explain coastline retreat in Vagueira Beach, the following multiple linear regression model was developed:

$$Retreat = \beta_0 + \beta_1 Groin5 + \beta_2 Dred3 + \beta_3 Precp \qquad (3)$$

where *Retreat* is the annual coastline retreat in Vagueira Beach (in m/year), *Groin5* the total length of groins built for the Espinho-Vagueira section at *t*+5 (in m), *Dred3* the annual dredging volume at the Aveiro Port entrance at *t*+3 (in 100,000 m^3/year), and where *Precp* is the annual precipitation (in mm/year).

Finally, the estimated regression model was validated using the Student *t*-test, the determination coefficient (R^2), the ANOVA F-test, and the variance inflation factor (*VIF*). The Student *t*-test was used to check whether signs and magnitude of the regression coefficients make sense in the context of the phenomenon being studied (Rummel, 2022). Furthermore, tests and confidence intervals (*t*-test and *F*-test) allow to obtain an indirect idea of the regression quality and confirm hypotheses of particular values for the parameters established by theoretical means.

The determination coefficient (R^2) represents a measure of adjustment of a statistical model in relation to the observed values. The R^2 indicates, in percentage terms, the extent to which the regression model explains the observed values. The closer the R^2 to 1, the larger the explanatory power or fit of the model (Hair et al., 2009).

The ANOVA *F*-test allows to evaluate the overall model, which in general is the statistical testing of the confidence of the coefficient of determination. Thus, if the *F*-test indicates a low level of significance (less than 5%), the data estimated by the regression model are close to those of the initially observed data.

Multicollinearity occurs when independent variables are strongly correlated, such that the interpretation of the contribution of predictors becomes difficult and the estimation of the regression coefficients is flawed. To test whether this occurs, the variance inflation factor (*VIF*) was calculated. A *VIF* > 10 indicates that the regression model shows problems of multicollinearity. The *VIF* is given by (O'Brien, 2007):

$$VIF = \frac{1}{1 - R^2} \qquad (4)$$

where *VIF* is the variance inflation factor of the regression model with a coefficient of determination R^2.

2.3. Results

2.3.1. Analysis of correlation between the factors related to coastline retreat

The retreat rate of the coastline is one of the best indexes of coastal erosion. It is a unique index and of exceptional value for the evaluation of coastline evolution tendencies as well as for the assessment of the real impacts of disruptive factors on coastal sediment dynamics (Coelho et al,, 2009b). In order to assess the relationship between the factors that can contribute to coastal erosion, correlation analysis was used to correlate the annual coastline retreat at Vagueira Beach with variables that are considered to influence coastal erosion—namely (Table 2.2): annual dredging, the total length of groins, and annual precipitation (as a proxy for storm events).

Table 2.2 - Correlation analysis between coastline retreat and possible factors that influence coastal erosion in Vagueira Beach.

Coastline retreat in Vagueira Beach		
Factors	Pearson's Correlation	Nº of Observations (evaluated years)
Dredging *t*+3	0.931***	27
Total length of groins *t*+5	0.891***	27
Precipitation	0.521***	22

Significant at the 1% (***) level

A high correlation was obtained between coastline retreat and the dredging at the Aveiro Port entrance (0.931), even though the port entrance is located around 10 km north of Vagueira Beach. The sediment dredged from the port entrance creates a deficit of sediment along the coastal stretch to the south. This lack of sediments is noticed in Vagueira Beach about 3 years after dredging (t + 3) at the Aveiro Port entrance (Figure 2.5).

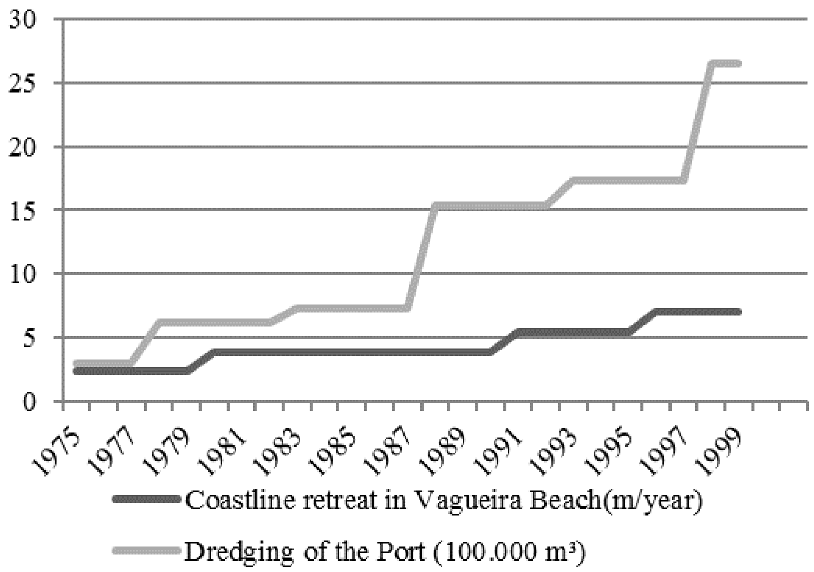

Figure 2.5 - Cumulative annual volume dredged at the Aveiro Port entrance and cumulative annual coastline retreat at Vagueira Beach over the period 1975–2000 (based on: EU, 2022).

The total length of groins also presents a high correlation with coastline retreat (0.891). Coastal protection measures are generally established in front and just south of urbanized areas (Dias et al., 1994). As with the dredging process, groins reduce sediment transport along the coast that, according to the correlation analysis, takes 5 years to be transported to Vagueira Beach (t+5).

Finally, the coastal area is influenced by oceanic, continental and atmospheric agents and, hence, its sensitivity to climate change (Neves & Muehe, 2008). Even though the correlation between coastline retreat and precipitation is relatively low (0.521), it seems that annual precipitation (and associated storm events) is a rea-sonable proxy for the energetic actions of the sea (see Figure 2.6). These actions have generated events of great impact that could jeopardize works of containment and coastal defense—leading to the relocation of sediments confined by coastal defense structures (Pereira & Coelho, 2013). Such relocation of sediments would, however, not result in recovery because there is a net sediment deficit (i.e., accretion is smaller than erosion; see Figure 2.2). In addition, although groins were sporadically and locally damaged over the years, groins are hard coastal structures that have been maintained over time and, thus, have preserved their full performance.

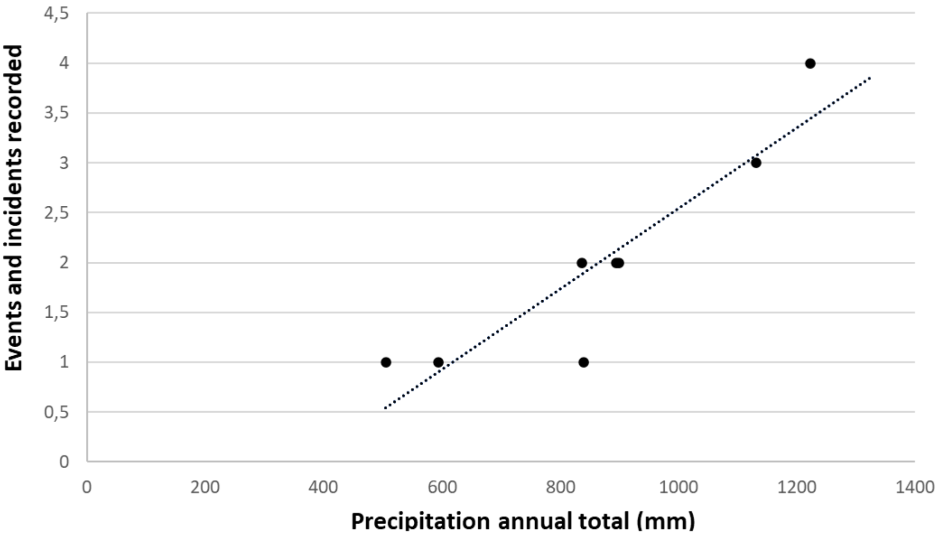

Figure 2.6 - Annual precipitation and recorded events & incidents of wave actions in Vagueira Beach (Pereira & Coelho, 2013; IPMA, 2022).

2.3.2. Assessment of factors related to coastal erosion through multiple linear regression

Regression simulation results (Table 2.3) show that the model has a very good fit (R^2 = 0.91). The ANOVA F-test (significant at 1%) indicates that values estimated by the regression model are close to the initial data of annual coastline retreat in Vagueira Beach, while the variance inflation factor (VIF) indicates that there is no problem of multicollinearity (VIF < 10).

Table 2.3 - Results for the multiple linear regression model of coastline retreat in Vagueira Beach.

Explanatory Variables	Coefficients			VIF
	Estimate	Weight	Student *t*-test	
Constant (β_0)	0.615		0.912	
Groin5 (β_1)	0.002	0.526	3.074 ***	5.773
Dred3 (β_2)	0.009	0.384	2.171 **	6.165
Precp (β_3)	0.001	0.130	1.611 *	1.280
R^2			0.91	
ANOVA *F*-test			59.79 ***	

Significant at the 1% (***), 5% (**) and 10% (*) level.

The analysis of the factors that explain annual coastline retreat allow a series of interpretations (Table 2.3). All factors have a positive sign, indicating that they are directly proportional to coastline retreat. The contribution of the total length of groins is the main factor responsible for coastline retreat in Vagueira Beach (*Groin5* with a weight of 53%), followed by the volume dredged at the Aveiro Port entrance (*Dred3* with a weight of 38%) and precipitation (*Precp* with a weight of 13%). Several authors argue that the weakening of sedimentary sources in the region is the biggest cause of coastal erosion problems (Dias et al., 1994; CEHIDRO/INAG 1998; Pereira & Coelho, 201; Coelho et al., 2009b). The reduction in sedimentary sources can explain the rates of coastline retreat observed in the region. This is in line with the obtained results, which show that groins and dredging reduce the transport of sediments and that over the years (after 5 and 3 years, respectively), this would settle on the coast in front of Vagueira Beach (Pereira & Coelho, 2013).

Student's t-test reveals that the total length of groins (*Groin5*) is the most significant factor (significant at the 1% level), followed by the volume dredged at the Aveiro Port entrance (*Dred3*; significant at the 5% level) proving, once again, the importance of sediment removal in explaining coastline retreat and confirming that human interventions lead to environmental changes. Finally, precipitation (*Precp*) is the least significant factor explaining coastline retreat (significant at the 10% level), indicating that annual precipitation, and associated storm events, only have a limited impact on shoreline retreat—albeit storm events cause significant damages to coastal infrastructures (see, e.g. Pereira & Coelho; 2013; Coelho et al., 2009b; Costa et al., 2001).

2.4. Discussion

Coastal erosion is one of the major management problems that coastal regions face worldwide (Phillips & Jones, 2006), and accurate information on coastline movement rates and trends is essential to support sustainable management strategies. Coastline retreat is a dominant trend along the Portuguese coastal zone, with a mean rate of retreat of 0.24 ± 0:01 m per year for the mainland (Lira et al, 2016). The central Portuguese coast, where Vagueira Beach is located, has suffered severe coastal erosion for decades—particularly along the sandy stretches. This process is related to anthropogenic transformations, a reduction in the supply of sediments, an increase in the mean sea level, and an increase in storm events (Maia et al., 2015).

The construction of coastal defense structures in Vagueira Beach began at the end of the 1970s and was accompanied by an increase in urban occupation (Maia et al., 2015). Hence, the density of the built area has increased significantly over the past decades - with the urban front increasing to 650 m in 2015. Along the coastline under analysis, coastal erosion has been addressed through the construction of protection structures, mainly groins, and dikes, which have had a negative impact on (beach) tourist demand. However, as the coastline retreat continues, it is expected that additional defense construction, maintenance, and emergency interventions will be needed with corresponding financial implications.

In the past, the sediments coming from continental sources, mainly rivers, would have the capacity to practically alone supply the sediments necessary for equilibrium (Coelho et al., 2009a). However, interventions such as the construction of dams in rivers north of Vagueira Beach (Pereira & Coelho, 2013; Lira et al., 2016), dredging at the Aveiro Port entrance (Pereira & Coelho, 2013; Pedrosa, 2013), and the construction of coastal defense structures (Maia et a., 2015; Pedrosa, 2013), pinpoint the underlying problem: the lack of sediment and subsequent coastal erosion. Several authors (see, e.g. Lira et al., 2016; Pinto et al., 2020; Coelho et al., 2007; Maia et al., 2015; Veloso-Gomes 2010) are unanimous in stating that the weakening of sedimentary sources is the major cause of erosion problems in the area under analysis (Coelho, 2005).

Climate change generates several impacts on the coastal zone, such as the potential rise in sea levels that puts further pressure on shoreline retreat (see, e.g. Roebeling et al., 2011a; Nicholls et al., 2007; Stefanova et al., 2015) as well as the increase in storm events that is expected to result in higher and also the altered direction of waves (see, e.g. Dias et al., 1994; Coelho et al., 2009b). As for precipitation, periods of drought alternating with periods of heavy precipitation, can lead to a decrease in river flows and, thus, less export of sediments by rivers to the coast (see, e.g. Pereira & Coelho, 2013; Stefanova et al., 2015).

2.5.Conclusions and Recommendations

This study assessed the influence of anthropogenic and natural factors on coast-line retreat in Vagueira Beach (Central Portugal). To this end, correlation and multiple linear regression analyses were applied. The main variables correlated with coastline retreat in Vagueira Beach were the total length of groins, annual dredging, and, to a minor extent, annual precipitation (as a proxy for storm events). These results are in line with other authors that highlighted the influence of sediment deficits on downdrift coastline retreat (Pereira & Coelho, 2013) associated with human interventions (such as dredging) and coastal structures (such as groins) (Pedrosa, 2013) as well as the influence of climatic factors (Dias et al., 1994; Coelho et al., 2009b).

Through the temporal distribution of several factors in the analysis, it can be concluded that the coastline retreat in Vagueira Beach has increased and is expected to maintain this trend in the near future if no other mitigation measures are considered. In particular, this is observed because of the groins constructed along the coastal stretch north of Vagueira Beach and the volume of material dredged at the Aveiro Port entrance, which has shown an increasing trend (Pereira & Coelho, 2013). In addition, climate change is expected to lead to sea-level rises and an increase in storm events over the next century (Roebeling et al., 2013; Coelho et al., 2007; Coelho et al., 2009b). Hence, the construction of groins along the coastal stretch north of Vagueira Beach should be carefully deliberated, while the recharge of materials dredged at the Aveiro Port entrance to beaches located south is increasingly being considered to mitigate coastal erosion on this coastal stretch (Coelho et al., 2007; Pereira & Coelho, 2013; Maia et al., 2015; Santos et al., 2022; Coelho et al., 2009b). In the meantime, local solutions in front of Vagueira Beach are assessed to halt and reverse coastline retreat in Vagueira Beach (Roebeling et al, 2011a; Roebeling et al., 2011b; Coelho, 2005; Neves & Muehe, 2008).

Some caveats remain. First, the use of annual precipitation as a proxy for storm events and associated wave actions has proven to work only reasonably well. A complete time series of actual wave action would be preferred, though the maritime wave records were too incomplete to be used for this purpose. Second, river sediment re-charge from the main river to the north of Vagueira Beach (in particular, from the Vouga River) would be an additional explanatory variable of importance, albeit most of the sediments from the Vouga River are trapped in the Aveiro Lagoon and Aveiro Port entrance. Finally, unlike other studies in this area, which focus on monitoring and modeling, this study provided an innovative statistical approach, based on correlation and regression analysis, to assess the causes and impacts of coastal erosion and can be easily replicated in similar coastal zones.

CHAPTER 3

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3. A global meta-analysis for estimating local ecosystem service value functions*

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ABSTRACT

The Meta-analysis has increasingly been used to synthesize the ecosystem services literature, with some testing of the use of such analyses to transfer benefits. These are typically based on local primary studies. However, meta-analyses associated with ecosystem services are a potentially powerful tool for transferring benefits, especially for environmental assets for which no primary studies are available. In this study we use the Ecosystem Service Valuation Database (ESVD), which brings together 1350 value estimates from more than 320 studies around the world, to estimate meta-regression functions for Provisioning, Regulating & maintenance, and Cultural ecosystem services across 12 biomes. We tested the reliability of these meta-regression functions and found that even using variables with high explanatory power, transfer errors could still be large. We show that meta-analytic transfer performs better than simple value transfer and, in addition, that local meta-analytical transfer (i.e., based on local explanatory variable values) provides more reliable estimates than global meta-analytical transfer (i.e., based on mean global explanatory variable values). Thus, we conclude that when taking into account the characteristics of the study area under analysis, including explanatory variables such as income, population density, and protection status, we can determine the value of ecosystem services with greater accuracy.

3.1. Introduction

Jean-Baptiste Say poses the idea of nature's services as costless, free gifts of nature as follows: "the wind which turns our mills, and even the heat of the sun, work for us; but happily, no one has yet been able to say, the wind and the sun are mine, and the service which they render must be paid for" (Say, 1829: p.124). However, currently it is possible to observe that the overuse or misuse of some natural resources poses direct impacts on society (TEEB, 2010). In the face of this problem came the concept of ecosystem services (ES), defined as the benefits that humans obtain from the natural environment and from properly functioning ecosystems. Hence, authors such as Bordt & Saner (2019), Browner, 2000, Constanza et al. 2014, de Groot et al. 2012, Díaz et al. 2015, Lindhjem & Navrud, 2008 and Navrud & Ready (2007) argue that sustainable management of natural resources requires correct valuation of the ecosystem defining their services to the society.

Ecosystem services support human life every day and contribute to human well-being in many ways, which are hard to define in a single notion. Hence, the Millennium Ecosystem Assessment (MEA, 2003) and the Common International Classification of Ecosystem Services (CICES, 2016) differentiate between the following ecosystem services: a) Provisioning services (such as supply of food via fishery production, fuel wood, energy resources, and natural products); b) Regulating & maintenance services (such as shoreline protection, nutrient regulation, carbon sequestration, detoxification of polluted waters, and waste disposal); and; c) Cultural services (such as tourism and recreation).

According to de Groot et al. (2012), ecosystems have great importance across many dimensions (ecological, socio-cultural, and economic). Thus, expressing the value of ecosystem services in monetary units (i.e., ecosystem service values; ESV), can prove to be of utmost im-portance to help raise consciousness and convey the (relative) importance of ecosystems and biodiversity to decision-makers. Indeed, monetized valuation pushes for more efficient use of limited resources and helps to select where protection and regeneration are economically more important and can be delivered at least cost (Crossman & Bryan, 2009; Crossman et al., 2011). It can also assist in determining "a fair compensation" to be paid for a loss of ES in liability regimes (Payne & Sand, 2011; as cited by de Groot et al. 2012)..

Historically, in the late 1990s and early 2000s, the concept of ES slowly found its way into the policy arena, e.g., through the "Ecosystem Approach" and the Global

Biodiversity Assessment. In 2005, the concept of ES gained wider interest after the publication of the Millennium Ecosystem Assessment by the United Nations for policymakers (MEA, 2003; Constanza et al., 2014). ES are also entering the consciousness of mainstream media and business, namely through the World Business Council for Sustainable Development that has actively supported and developed this concept (WBCSD, 2012). Many projects and groups are currently working toward better understanding, modeling, valuing, and managing ES and natural capital (Constanza et al., 2014).

An increasing number of papers seeking the valuation of ES have been published over the last decades. Assessments have been conducted at local (e.g. Maynard et al., 2010; Van Houtven et al., 2007; Schröter et al., 2014), national (e.g. Perez-Verdin, 2016; Schröter et al., 2016; Alves, 2009), continental (e.g. Paprotny et al., 2021; Roebeling et al. 2013) and global (e.g. Díaz et al., 2015; Costanza et al., 2014; de Groot et al., 2012) scales. In the same way, databases compiling data from these primary valuation studies were created to aggregate information and facilitate public debate and policy action. Some examples of such databases include the Economic Valuation Reference Inventory (EVRI, 2017), Ecosystem Service Values (ESValues, 2020) and the Ecosystem Service Valuation Database (ESVD, 2020).

Since the early 1990s, several researchers have investigated the applicability and the precision of benefit transfer. However, these past studies were primarily concerned with traditional methods of benefit transfer (in particular value transfer), replacing values directly from the study site to the policy site without amendments (Rosenberger & Loomis, 2000). However, in the late 1990s meta-analysis started to be used, with multivariate regression being investigated for use in benefit transfer (Desvousges et al., 1998).

The meta-analysis (MA) is a technique that uses statistical models (meta-regressions) to summarize and evaluate previous research results. In benefit trans-fer, meta-regression results may be used qualitatively, to corroborate new primary results, or to transfer estimated values (Hoehn, 2006). Meta-regression in benefit transfer summarizes the weight of the evidence and characterizes the degree of uncertainty about quality-adjusted ecosystem values. In meta-regression, the value estimates from primary valuation studies are thereby treated as individual observations (Smith & Pattanayak, 2002). Meta-regression also extends the range of primary valuation studies by allowing the estimation of values for services and functions that are constant within each primary valuation study but vary across different valuation studies (Johnston et al., 2005).

Meta-analyses have been performed for specific ecosystem services, biomes, and locations. For example, Van Houtven et al. (2007), assessed the cultural value of surface water quality in the United States, using 131 willingness-to-pay (WTP) estimates from 18 studies. Similarly, Hjerpe et al. (2015) synthesized 127 WTP estimates from 22 different studies that provided estimations for preservation, forest restoration, and fresh-water restoration also in the United States. Ghermandi et al. (2010) performed a meta-analysis to determine the values of goods and services provided by wetland ecosystems, using 418 value observations derived from 170 valuation studies and 186 wet-land sites worldwide. Finally, Hynes et al. (2018) performed a marine recreational me-ta-analysis estimation, using 311 distinct value observations from 96 primary valuation studies. Nevertheless, there are no studies with a broader analysis, that estimate global meta-regression functions for Provisioning, Regulating & maintenance and Cultural ecosystem services across biomes and continents. In addition, testing the reliability of estimated meta-regression functions is relatively rare, (e.g. Ready & Navrud, 2006; Subroy et al. 2019). One of the main challenges is developing equations for ES that capture the local/regional characteristics of the biome and provide reliable value estimates.

Hence, the objective of this study is to estimate meta-regression functions for 3 different types of ecosystem services able to determine the ecosystem service value for 12 different types of biomes, with the possibility of these estimates being applied at the global scale. In this study, we provide the results of a meta-analysis based on the primary value estimates from the Ecosystem Service Valuation Database (ESVD, 2020) for 3 ecosystem services (Provisioning; Regulating & maintenance; Cultural), provided by 12 main land covers (Coastal systems; Coastal wetlands; Coral reefs; Cultivated areas; Desert; Fresh water; Grasslands; Inland wetlands; Open Ocean; Temperate/Boreal forests; Tropical forests; Woodlands). In addition, complementary explanatory variables from the World Bank Data (World Bank, 2020) and FAOSTAT (FAOSTAT, 2020) were gathered. Based on this re-view and meta-analysis, we aim to provide recommendations for future research that may enhance the use of ecosystem service valuation for policy analysis.

The remainder of this chapter is structured as follows. The “Materials and Methods” section details the MA application and use in ES studies, the theoretical specification and validation method and, finally, the ESVD database and other variables used to build the models. In turn, in the “Results” section, we expose and analyze the functional forms of the models for the three ecosystem services, present the application of the models, and discusses the results.

3.2.Conceptual Framework

3.2.1. Literature on Meta-analysis

Benefit transfer (BT) is an economic valuation tool, with the goal to adapt value estimates from past research to assess the value of a similar, but separate, change in a different resource (Smith et al., 2002). Technically, BT uses valuation estimates from other areas (study sites) and applies them to a similar location (policy site; Brouwer, 2000). It’s a technique that relies on primary studies and, therefore, allows for the reduction of field research constraints, both in terms of time and infrastructure. However, it can lead to over/underestimated values while the accuracy of an ESV estimate is determined by the quality of the reference studies used. Thus, peer reviewed empirical studies from similar biophysical and socioeconomic contexts are preferred over any other type of data source (Ready & Navrud, 2006).

BT is useful when the estimation of the economic service value cannot be obtained due to time and/or budget constraints and to, therefore, make the best possible use of the existing literature in order to evaluate the economic importance of a natural area (Alves et al., 2009). This is possible by adopting and applying estimates from existing studies that best suit the new context, using one or more of the following BT methods: (i) benefit estimate or value transfer, which is the extrapolation of estimates from one site to another (i.e., values are directly transposed from the study site to the policy site without amendments), (ii) benefit function transfer, which is the transfer of economic functions between the sites (i.e., coefficients are used to determine the policy site values), (iii) meta-analysis, which combines the findings of independent studies related to the research topic as to summarize the body of evidence relating to a particular issue, and (iv) preference calibration, which uses existing benefit estimates derived from different methodologies and combines them to develop a theoretically consistent estimate for policy site values (Bergstrom & De Civita, 1999).

The Meta-Analysis (MA) technique can help reduce deviations in value estimates (Hoehn, 2006). This technique was first put forward by Glass (1976), as a research synthesis method, and has since been developed and applied in many fields of research, other than the area of environmental economics (Nelson & Kennedy, 2009). It is widely recognized that the large and increasing literature on economic valuation of ES and environmental impacts has become difficult to interpret and that there is a need for research synthesis, especially in statistical MA, to aggregate information and insights (Stanley, 2001; Smith & Pattanayak, 2002; Bateman & Jones, 2003).

MA is by definition a quantitative analysis of statistical summary indicators reported in a series of similar empirical studies. It’s a commonly used method for compiling and analyzing the data from studies towards the creation of a value function. This is a method of synthesizing the results of multiple studies that examine the same phenomenon, through the identification of a common effect, which is then “explained” using regression techniques in a meta-regression model (Stanley, 2001). In the realm of environmental resource valuation, MA is commonly used in benefit transfer endeavors due to its usefulness in incorporating a structural utility framework with less strictly economic information (Smith & Pattanayak, 2002; Bergstrom & Taylor, 2006).

3.2.2. Specification of the Meta-regression

Based on consumer rationality and reasonableness, the microeconomic consumer theory is explained by two different approaches: the indifference curve approach and the utility function approach (Pindyck & Rubinfeld, 2005). Indifference curves represent all combinations of goods and services that provide the same level of satisfaction to an individual (i.e., the same level of global utility). Implicit in an indifference curve is the marginal rate of substitution, which expresses the maximum amount of a good that one is willing to give up in exchange for one additional unit of another good, at the same level of satisfaction (Pindyck & Rubinfeld, 2005). Utility functions represent the degree of profitability or satisfaction that we get from using goods and services, related to a measure of satisfaction relative to an economic agent. The analysis of its variation allows for explaining the behavior that results from the decisions taken by each agent to increase his/her satisfaction.

Any meta-analytic benefit transfer (MA-BT) must be based on the ecosystem service valuation theory and the utility functions theory (see Eq. 1), specific to microeconomics (Bergstrom & Taylor, 2006). The general form of a MA-BT underlying the utility function, is given by (Rosenberger & Loomis, 2000):

$$U_i = f(P_i, Y_i,\ Q_i, Ql_i, Sub_i, H_i, I_i) \tag{1}$$

where U_i is the utility (satisfaction) obtained by individual i, P_i is the general price level faced by individual i, Y_i is the individual revenue, Q_i is the quantity of ES available to individual i, Ql_i is the global quality of ES available to individual i, Sub_i represents the substitutes for Q available to individual i, H_i refers to other non-income attributes of individual i, and I_i is the information available to individual i.

Resorting to this microeconomic theoretic, we organize the MA-BT utility theory into three axes: the “strong structural utility theoretic (SSUT) approach”, the “weak structural utility theoretic (WSUT) approach” and the “non-structural utility theoretic (NSUT) approach” (of which they only endorse the first two) (Bergstrom & Taylor, 2006).

Following the microeconomics reasoning, we assume that MA-BT is based on the utility function (see Equation (2)) and opt for analyzing the WSUT. Under the WSUT, each individual may choose between two alternative environmental options—ceteris paribus, a damaged ecosystem (Q_0) and a restored ecosystem (Q_1), which will assure an equilibrium situation (the maximum utility) (Bergstrom & Taylor, 2006; Lindhjema & Navrud, 2008), represented by:

$$U_i\,(P_i, Y_i, Q_0) = U_i\,(P_i, Y_i, -ESV, Q_1) \tag{2}$$

where U_i is the utility obtained by individual *i*, P_i is general price level faced by individual i, Y_i is individual revenue, Q_0 quality/quantity of ES available to individual *i* in the absence of any payment, *ESV* is ecosystem service value paid by individual *i*, and Q_1 is the quality/quantity of ecosystem available to individual *i* after having paid for these ES.

Microeconomics utility theory will hold if both sides of this parity are equal. That is, an individual will stay at the same indifference curve if he/she gets the same level of satisfaction by consuming Q_0 with no payment or by consuming Q_1 and paying ESV in exchange. That is, the ESV the individual is willing to give-up must be counterbalanced by an increase in Q. Thus, $Q_1 > Q_0$ after the amount has been spent.

In this study, we adopt the WSUT approach, where variables are added in the bid-function (assumed to be derived from some unidentified utility function) but keeping the flexibility to incorporate other explanatory variables into the ESV model, such as study-site characteristics, local price levels or local individual income (Lindhjema & Navrud, 2008). This is the approach used in most previous MA-BT studies (Lindhjema & Navrud, 2008; Rao et al. 2015; Hynes et al. 2018). Our general theoretical model will focus on estimating the ESV (see Equation (3)), as a function of various ex-planatory variables according to the general form of the underlying conditional indirect utility function:

$$ESV = f(B_l, SQ_l, C, QQ_r, I_r, P_r) \tag{3}$$

where, B_l is the biome and SQ_l the quality status for the location under analysis (l), C is the continent where the study area is located, and QQ_r is the quality/quantity of protected areas, I_r is the income and P_r is population density in the region (r) where the study area is located.

The meta-modelling approach has several advantages for BT as compared to other methods (such as value transfer or function transfer). Different from those, which are based on single studies, MA resorts to information from a collection of studies and, thus, provides more rigorous measures of central tendencies that are sensitive to the distributions of underlying study values (Rosenberger & Loomis 2000).

3.2.3. Validity and reliability of a meta-analytic benefit transfer

The validity and reliability of the MA-BT can be assessed by applying the concept of transfer error (TE), defined as (Ready & Navrud, 2006):

$$TE = \frac{|ESV_P - ESV_B|}{ESV_B} \tag{4}$$

where ESV_P is the predicted value from the study site (s) and ESV_B is the base value ("benchmark") at the policy site. The *TE* is often used as a validity measure of the acceptability of meta-models. Traditionally, validity requires that the values, or the value functions generated from the study site, be statistically identical to those estimated at the policy site (Navrud and Ready, 2007). The main objective is to find a target value of $TE=0$, confirming that the estimated values from the MA-BT values are similar to those arising from the database.

There is no agreement on maximum TE levels for BT being reliable for different policy applications. The TE analysis is not supposed to judge which levels should be considered acceptable, or even conduct traditional statistical tests of BT validity. In-stead, it remains a measure of reliability, especially if TE estimates are compared across meta-model specifications and restrictions, and between alternative ways of conducting BT based on the same data (Lindhjema & Navrud, 2008).

Therefore, we perform the following comparisons between the estimates from the meta-model and the original observations from the database:

(a) "Value transfer" compares each ESV estimate in the database with the corresponding global mean ESV;

(b) "Global meta function transfer" compares each ESV estimate in the database with the estimates produced by the meta-model, using mean global values for the explanatory variables;

(c) "Local meta function transfer" compares each ESV estimate in the database with the estimates produced by the meta-model, using mean national values for the explanatory variables.

3.3. Background and data

MA in environmental valuation is, generally, based on brief statistics and analytical conclusions taking a group of studies as data. Therefore, MA estimates can reduce the time spent to acquire data—both in the case of older studies and unpublished work (where data may not be available) and current studies (where authors may be slow to disclose data). However, even within the same methodology, combining primary data is not always possible due to conflicting data structures and different estimation procedures (Bergstrom & Taylor, 2006). This might limit the MA studies' representativeness.

A solution to this problem is the use of specialized ESV databases, which offer a wide range of detailed information about the studies taken into account, beyond the results found in the assessment. These databases give information on other factors crucial for the delimitation of a MA model, such as: the year of the study, protection status, location, type of environment, and method. In this analysis, we use the Ecosystem Service Valuation Database (ESVD, 2020), one of the biggest databases containing real values for a range of ES and biomes where the value estimates are systematized in monetary units (€/ha/year).

The ESVD was built to process and analyze the monetary estimates of ES values from different biomes in a way that it is easily used by various end-users, worldwide. Composed by 267 studies and 1310 value estimates, the ESVD links various types of information from different studies with the value estimates and case study sites. These value estimates are organized by biome, ES and country. The main biomes are "Coastal System" (*CSys*), "Coastal Wetland" (*CWet*), "Coral Reef" (*CoRf*), "Cultivated Area" (*CuAr*), "Desert" (*Dser*), "Grassland" (*Gras*), "Inland Wetland" (*InWt*), "Marine" (*Mari*), "Temperate or Boreal Forest" (*TeFo*), "Tropical Forest" (*TrFo*), "Fresh Water" (*FrWa*) and "Woodland" (*Wood*). The ES are Provisioning; Regulating & Maintenance and; Cultural services, divided in 14 types of services (see in Figure 1). Finally, a total of 80 countries are included, 217 values from Africa; 352 values from Asia, 208 values from Europe, 180 values from Latin America and the Caribbean; 122 values from North America, 116 from Oceania, and 114 from the whole world.

Initial criteria for selecting studies from the general ESVD database were: (1) original nature of the case study data (i.e., not based on value transfer or total ecosystem value); (2) the provision of a complete set of information, including the study site location, surface area and the scale of the study (i.e., not based on a "world" scale location); (3) clear characterization of valuation methodologies used (i.e., not unknown valuation methods); (4) clear mentioning of the surface area for which the ecosystem service valuation study is applied (so that estimates of monetary values per hectare can be obtained); and (5) ES or sub-service monetary value directly linked to a specific biome/ecosystem and unit (i.e., not per person or household). Besides information on the location of each case study, the ESVD includes information on protection status and the size of the research area, enabling for the verification of whether more estimates about the same case study location are available from other sources or publications. Together with supplementary variables, coming from complementary socio-economic databases that are added to ESVD, these variables allow for further socio-economic interpretation of the monetary output values.

In order to relate an estimate of an ecosystem service to the socio-economic context of a case study site, two additional variables were included in the country table – namely the Gross national income (*GNI*) per capita (based on purchasing power parity in current international prices) and the average Population density (*PDen*; people per square kilometer). This information was obtained from the World Bank Data, which provides world development indicators by country (World Bank, 2020). Collected values were obtained for the years in which the studies were carried out.

Regarding protection status, many of the data points in the ESVD pertain to case studies in protected areas. This information allows the assessment of the influence of the protection status on ES value, testing whether protection excludes the user's access to the site and consequently to the services generated or, alternatively, whether it allows for ecosystem conservation and subsequent appreciation of the services. Protection status is classified into 3 categories: Fully protected (*FProt*), Partially protected (*PProt*) or Not protected (*NProt*). Other complementary variables collected from the World Bank Data, used to verify the study-site protection status, were: Terrestrial Protected Areas (*TProt*; the percentage of protected land by country) and Marine Protected Areas (*MProt*; the percentage of protected territorial waters). From the Food and Agriculture Organization (FAO) statistical database (FAOSTAT, 2020), information on the land use characteristics was collected. Namely, the percentage of forest area (*FPer*) and the percentage of agricultural land (*APer*), which helped to understand land use and occupation characteristics with emphasis on agricultural activities and state of preservation/conservation of nature.

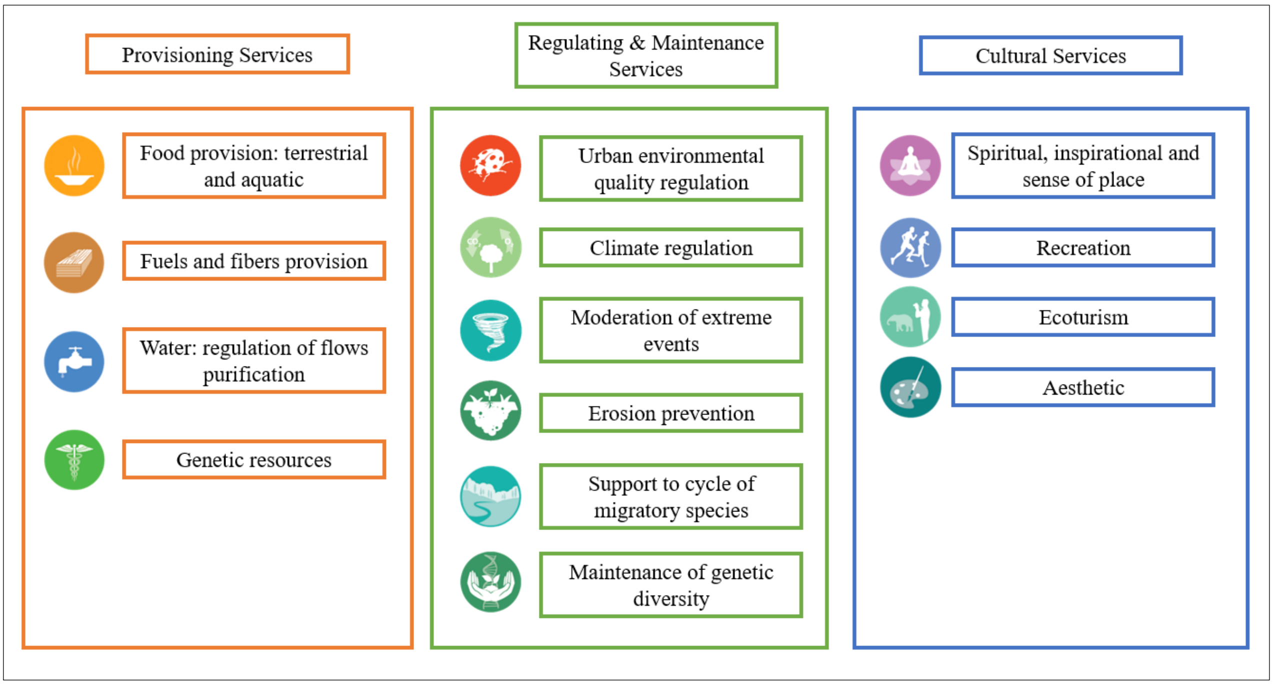

Figure 3.1 - Ecosystem service values division (Adapted from FAO, 2009).

For each biome in the ESVD, 14 ecosystem services were identified and classified into the 3 main classes: Provisioning, Regulating & maintenance, and Cultural services (see (Figure 3.1). This classification constitutes an important step in the linkage between ES and human well-being and will be used as a basis to perform MA-BT for ecosystem valuation. Provisioning services (ESV_{Prov}) are mainly composed of food provision, water provision (including regulation of water flows and water purification), fuels and fibers provision, and genetic resources provision (FAO, 2009). This is an ES highly valued by humans, because of the direct impact on our day-to-day life. Regulating & maintenance services ($ESV_{Reg\&Main}$) help maintaining air, climate, and water quality, moderating extreme events, maintaining soil quality, and preventing erosion. Albeit usually invisible and taken for granted, they are important for human well-being and the conservation of plants and animals (FAO, 2009). Finally, cultural services (ESV_{Cult}) entail non-material benefits that people obtain from an ecosystem, such as aesthetic inspiration, recreation, and tourism as well as spiritual experience related to a natural environment (FAO, 2009).

All monetary values in the ESVD values are converted into a common reference unit, specifically 2015 ‘International’ €/ha/year, using the Purchasing Power Parity (PPP) units expressed in Euros (FAO, 2009; World Bank, 2020).

3.4. Data summary

Based on the above-mentioned criteria, the total number of monetary value estimates included in our sample amount to 636 observations. In this study, ES value functions are estimated for Provisioning, Regulating & maintenance, and Cultural services (see Section 3.5). The estimation of each ES value function draws on a different number of observations (Table 3.1): Provisioning services (302; 47.5%), Regulating & maintenance services (225; 35.4%), and Cultural services (109; 17.1%).

Table 3.1 - Number of valuation studies, by service1 and biome2, from the ESVD included.

Service[1] /Biome[2]	*CSys*	*CWet*	*CoRf*	*CuAr*	*Dser*	*FrWa*	*Gras*	*InWt*	*Mari*	*TeFo*	*TrFo*	*Wood*	Total
Prov.	18	55	37	6	2	5	10	75	6	8	63	17	302
Regu. & Main.	6	58	26	7	-	1	9	36	4	16	51	11	225
Cult.	7	14	42	-	-	4	2	11	4	10	14	1	109

Note: [1] *CSys* = Coastal System; CWet = Coastal Wetland; CoRf = Coral Reef; CuAr = Cultivated Area; Dser = Desert; FrWa = Fresh Water; Gras = Grassland; InWt = Inland Wetland; Mari = Marine; TeFo = Temp./Bor. Forest; TrFo = Tropical Forest; Wood = Woodland.

[2] ESV_{Prov} = Provisioning Ecosystem Values; $ESV_{Reg\&Main}$ = Regulating & Maintenance Ecosystem Values; ESV_{Cult} = Cultural Ecosystem Values; ESV_{Total} = Total Ecosystem Services Values.

Table 3.2 lists and describes the main variables used in the MA. Table 2.3 provides summary statistics for each of these variables for every service, with exception for the dummy variables.

Table 3.2 - Meta-Analysis Variables Description.

Variables	Description
APer	Agricultural land that refers to the share of land area that is arable, under permanent crops, and under permanent pastures, by percentage of land area.
FPer	Forest area with natural or planted stands of trees of at least 5 m in situ, by percentage of land area.
MProt	Percentage of marine protected areas, from territorial waters of a country.
TProt	Percentage of terrestrial areas totally or partially protected, designated by national authorities.
GNI	Gross National Income per capita, using purchasing power parity rates.
PDen	Population density is midyear population divided by land area in square kilometers.
Dummies	
CSys; CWet; CoRf;	**Biomes:** Coastal System; Coastal Wetland; Coral Reef;
CuAr; Dser; FrWa;	Cultivated Area; Desert; Fresh Water;
Gras; InWt; Mari;	Grassland; Inland Wetland; Marine;
TeFo; TrFo; Wood	Temp./Bor. Forest; Tropical Forest; Woodland.
Euro; Asia; Ocea;	**Continents:** Europe; Asia; Oceania;
LaAm; NoAm; Afric	Latin America and Caribbean; North America; Africa.
FProt; PProt; NProt	**Protection Status:** Fully Protected; Partially Protected; Not Protected.

Table 3.3- Summary statistics for meta-regression variables in ecosystem services.

Variables[1]	Mean	Stand. Dev.	Min	Max
Provisioning Services				
TProt	14.94	8.53	0.00	6.27
APer	42.78	18.99	6.27	80.89
PDen	124.60	143.77	1.70	1 130.40
GNI	7 481.06	10 021.30	430.00	44 740.00
Regulating & Maintenance Services				
FPer	35.20	20.57	0.24	91.34
MProt	12.54	17.12	0.00	74.70
TProt	14.73	7.56	0.00	36.84
PDen	115.70	127.07	2.40	502.30
GNI	14 471.44	14 036.35	430.00	48 420.00
Cultural Services				
MProt	15.52	17.63	0.00	74.82
PDen	105.23	116.90	2.30	478.30
GNI	16 750.05	13 484.39	840.00	48 420.00

Note: [1] See Table 3.2 for variable descriptions.

The common variables in all models (Provisioning; Regulating & maintenance; Cultural) are Population density (*PDen*) and Gross national income per capita (*GNI* see

Table 3.3). These variables show the largest mean, minimum, and maximum dispersion, representing the large differences in population and wealth in countries around the world. Additional variables were created to describe potentially influential study site characteristics. In the case of Provisioning services, these were: the agricultural areas (*APer*) and the terrestrial protected areas (*TProt*). The former represents the food, fuels, and fibers provisioned, and the latter represents regulation of flows and purification provided. In the case of Regulating & maintenance services, these were: the forest areas (*FPer*) and the terrestrial (*TProt*) and marine (*MProt*) protected areas. These variables express the quality/quantity of natural resources that directly influence their prevention, moderation, and support. In the case of Cultural services, these were the marine protected areas (*MProt*), which represent quality, namely related to the sea.

3.5. Meta-regression model specification

We adopt a semi-log functional form specification for the ES value functions, which implies that the marginal effect of a change in ESV depends on income and population density (Van Houtven et al., 2007).

The Provisioning ES value function is determined by the type of biome (D_{Biome}), location of the continent ($D_{Continent}$), terrestrial protected area (*TProt*; following Agardy, 1994), percentage of agricultural land (*APer*; following De Beurs & Henebry, 2004), population density (*PDen*; following de Groot et al., 2012), and income (*GNI*; following Van Houtven et al., 2007), and given by:

$$\ln(ESV_{Prov}) = \alpha_0 + \alpha_1 * D_{Biome} + \alpha_2 * D_{Continet} + \alpha_3 * TProt + \alpha_4 * APer + \alpha_5 * \ln(PDen) + \alpha_6 * \ln(GNI) \qquad (5)$$

where α_0 is a constant, α_1 and α_2 are dummy regression estimates, and α_3 to α_6 are variable regression estimates.

The Regulating & maintenance ES value function is determined by the type of biome (D_{biome}), location of the continent ($D_{Continent}$), level of protection in study area (*FProt*, following Van Houtven et al., 2007), the terrestrial (*TProt*) and marine (*MProt*) protected area (following Agardy, 1994), percentage of Forest land (*FPer*; following De Beurs &

Henebry, 2004), population density (*PDen*; following de Groot et al., 2012), and income (*GNI*; following Van Houtven et al., 2007), and given by:

$$\ln\left(ESV_{Reg\&Main}\right) = \beta_0 + \beta_1 * D_{Biome} + \beta_2 * D_{Continet} + \beta_3 * FProt + \beta_4 * FPer + \beta_5 * MProt + \beta_6 * TProt + \beta_7 * \ln(PDen) + \beta_8 * \ln\,(GNI) \quad (6)$$

where β_0 is a constant, β_1 and β_2 are dummy regression estimates, and β_3 to β_8 are variable regression estimates.

Finally, the Cultural ES value function is determined by the type of biome (D_{biome}), location of the continent ($D_{Continent}$), level of protection in study area (*PProt*; following Van Houtven et al., 2007), marine protected area (*MProt*; following Agardy, 1994), population density (*PDen*; following de Groot et al., 2012), and income (*GNI*; following Van Houtven et al., 2007), and given by:

$$\ln(ESV_{Cult}) = \gamma_0 + \gamma_1 * D_{Biome} + \gamma_2 * D_{Continet} + \gamma_3 * \text{PProt} + \gamma_4 * MProt + \gamma_5 * \ln(PDen) + \gamma_6 * \ln\,(GNI) \quad (7)$$

where γ_0 is a constant, γ_1 and γ_2 are dummy regression estimates, and γ_3 to γ_6 are variable regression estimates.

3.6. Meta-regression model results

Table 3.4 reports regression results for two model specifications; the “Full” model in which all variables are included and the “Restricted” model in which non-significant explanatory variables were excluded in a stepwise procedure (applying a cut-off significance level of 20% for the *t*-test). The following base values for the dummies are considered: Grasslands (*Gras*) for biomes; Not protected (*NProt*) for protection status; and Europe (*Euro*) for continents.

Table 3.4 - Meta-regression results (ESV_{Prov}; $ESV_{Reg\&Main}$; ESV_{Cult}).

Explanatory variables^1	Model specification											
	Provisioning Serv. Model				**Regu. & Main. Serv. Model**				**Cultural Serv. Model**			
	Full		Restricted		Full		Restricted		Full		Restricted	
	Coef	*t (sig)*	*Coef*	*t (sig)*	*Coef*	*t (sig)*	*Coef*	*t (sig)*	*Coef*	*t (sig)*	*Coef*	*t (sig)*
CONSTANT	-3.80	0.36	-6.41	0.01	-7.97	0.03	-3.46	0.19	-12.37	0.07	-7.37	0.03
CSy	1.93	0.19	2.68	0.01	5.10	0.01	3.98	0.01	2.09	0.40	-	-
CWet	1.51	0.24	2.22	0.01	5.31	0.01	4.19	0.01	4.70	0.05	1.35	0.20
CoRf	-0.85	0.53	-	-	5.28	0.01	4.68	0.01	5.83	0.01	2.48	0.01
CuAr	3.07	0.11	3.69	0.01	4.28	0.01	3.07	0.01				
Dser	1.24	0.66	-	-								
FrWa	1.41	0.49	2.17	0.19	2.79	0.28	-	-	7,08	0,00	-	-
Gras^2	-	-	-	-	-	-	-	-	-	-	-	-
InWt	1.29	0.31	2.03	0.01	5.53	0.01	4.77	0.01	5.04	0.04	1.48	0.20
Mari	1.08	0.57	2.18	0.15	2.07	0.17	-	-	1.44	0.58	-2.47	0.12
TeFo	-1.46	0.42	-	-	4.80	0.01	3.35	0.01	0.81	0.75	-3.09	0.01
TrFo	1.37	0.29	2.06	0.01	3.47	0.01	2.40	0.01	4.80	0.04	1.20	0.20
Wood	-0.33	0.83	-	-	1.69	0.12	-	-	6.28	0.08	-	-
FProt	-0.18	0.80	-	-	-1.83	0.01	-1.73	0.01	-0.42	0.75	-	-
PProt	-0.25	0.66	-	-	-0.24	0.63	-	-	0.78	0.53	1.17	0.05
NProt^2	-	-	-	-	-	-	-	-	-	-	-	-
Euro^2	-	-	-	-	-	-	-	-	-	-	-	-
Asia	-1.05	0.44	-	-	0.43	0.59	-	-	-1.09	0.49	-1.75	0.06
Ocea	-0.77	0.60	-	-	1.53	0.13	-	-	-0.81	0.59	-1.33	0.16
LaAm	0.82	0.55	1.76	0.01	1.14	0.23	-	-	2.55	0.17	1.33	0.18
NoAm	-0.97	0.53	-	-	0.66	0.41	-	-	0.98	0.46	-	-
Afric	-1.20	0.45	-	-	-0.79	0.49	-2.12	0.01	0.66	0.74	-	-
APer	-0.04	0.02	-0.04	0.01	-	-	-	-	-	-	-	-
FPer	-	-	-	-	-0.01	0.24	-0.02	0.05	-	-	-	-
Mprot	-0.02	0.33	-	-	-0.02	0.25	-0.02	0.19	-0.06	0.01	-0.05	0.01
TProt	-0.05	0.14	-0.05	0.10	-0.04	0.15	-0.05	0.06	-0.03	0.40	-	-
ln_*GNI*	0.81	0.01	0.87	0.01	0.65	0.02	0.49	0.03	1.21	0.02	1.04	0.01
ln_*PDen*	0.54	0.03	0.59	0.01	0.91	0.01	0.66	0.01	0.53	0.12	0.48	0.09
N	302				225				109			
***R*²**	0.20		0.19		0.47		0.46		0.48		0.38	
***p*- Value ^{3}**	0.01		0.01		0.01		0.01		0.01		0.01	

Notes: Dependent variable is ln_ESV_i. ^{1} See Table 3.2 for variable descriptions. ^{2} variable used as the basis for analysis of the dummies;^{3} F-test of joint restriction that coefficients of excluded variables are equal to zero.

The main explanatory variables presented in all “Restricted” models were Population density (*ln_PDen*) and Gross national income (*ln_GNI*), with positive coefficient values and high significance (t-test < 0.09), which implies that an increase in population or income results in an increase ESV. As we adopt the logarithmic form for these variables, the marginal increase in ESV is decreasing in population or income.

We adopted additional explanatory variables for environmental quality, being *MProt* and *TProt* the percentage of, respectively, terrestrial and marine protected areas. Specifically, for the Provisioning model the *APer* (percentage of agricultural land) and for the Regulating & maintenance model the *FPer* (percentage of forest land) were used.

The Provisioning ES model provides a reasonable fit to the data, although it is the model with the smallest R^2 (0.19) and with the statistics of 0.01 in ANOVA for the restricted model. The signs of the explanatory variables are, as expected, positive for D_{biome}, *LaAm*, *ln_PDen*, and *ln_GNI*, and negative for *TProt*. This confirms that the other land covers analyzed tend to have a higher value than Grasslands (used as a base for the dummy biomes) and that areas located in Latin America generate larger provisioning ecosystem service values, while the ecosystem service value decreases with an increase in the percentage of protected terrestrial area. The variable *APer* is an exception (*Coef* = −0.04 and t-test < 0.01), presenting a negative coefficient, for which a positive sign was expected—which could be explained by the fact that countries with larger agricultural areas present a greater supply of provisioning services, though lower productivity levels. Significant explanatory variables present t-test < 0.19, the remaining variables were dropped. Evaluating the dummy variables for biomes, the one that presented the highest coefficient for the ESV_{Prov} was *CuAr* (*Coef* = 3.69 and t-test < 0.01), indicating that Cultivated areas is the key variable explaining provisioning service values.

The Regulating & maintenance ES model provides a good fit to the data, being the model with the highest R^2 (0.46) and with the statistics of 0.01 in ANOVA for the restricted model. The sign of the explanatory variables is as expected positive for D_{biome}, *ln_PDen*, and *ln_GNI*, and negative for *AFric*. This confirms that, as mentioned before, the other land covers analyzed tend to have a higher value than Grasslands and that areas located in Africa tend to have a lower value for this type of service (due to the lower aggregate income). The variables related to nature protection: *FProt* (*Coef* = −1.73 and t-test < 0.01), *FPer* (*Coef* = −0.02 and t-test < 0.05), *MProt* (*Coef* = −0.02 and t-test < 0.19) and *TProt* (*Coef* = −0.05 and t-test < 0.05), present negative coefficients, for which a positive sign was expected, revealing the theory that protected areas, which generally have low population density or are even inaccessible to the population, represent a low monetary value (i.e., people do not fully perceive the value of this service being generated). Significant explanatory variables present *t*-test < 0.19, the remaining variables were dropped. In the $ESV_{Reg\&Main}$ the largest coefficient for biome was observed in *InWt* (*Coef* = 4.77 and *t*-test < 0.01), although many others such as *CoRf*, *CWet*, and *CSys*, (*Coef* = 4,68; 4,19; 3,98 and *t*-test < 0.01, respectively) also presented high values, these biomes hold a series of important services, such as climate moderation, erosion prevention, maintenance, and support for different species.

The Cultural ES model also presents a good fit to the data, with an R^2 (0.38) and with the statistics of 0.01 in ANOVA for the restricted model. The sign of the explanatory variables is as expected positive for *PProt*, *ln_PDen*, and *ln_GNI*, *LaAm* and negative for *MProt*, *Asia*, *Ocea*. This explains that partially protected areas make it possible for people to access and benefit from the services generated. Moreover, Latin America is the area that presents the largest Cultural ES (primary studies mainly from the Caribbean coast). The D_{biome} variables *Mari* (*Coef* = −2.47 and *t*-test < 0.12) and *TeFo* (*Coef* = −3.09 and *t*-test < 0.01), present negative coefficients, for which a positive sign was expected, due to the small number of studies related to cultural services involving these land covers in the ESVD. In the ESV_{Cult} the largest coefficient was *CoRf* (*Coef* = 2.48 and *t*-test < 0.01), explaining the high value of services associated with the Coral reefs biome, which provides services such as ecotourism, recreation, and aesthetics, receiving thousands of tourists annually.

The model with the least good fit was the Provisioning ES model ($R^2 = 0.19$), followed by the Cultural ES model with a reasonable fit ($R^2 = 0.38$) and the Regulating & maintenance ES model" with a reasonably good fit ($R^2 = 0.46$) for the restricted models. Although these values are low as compared to other ESV meta-analysis studies (Table 3.5), a great variability is observed in these studies, with R^2 between 0.25 and 0.87. The explanation for these values is related to the large number of observed studies that presented different characteristics like the location, valuation method, and different years in which the study was performed. For example, the studies conducted by Rosenberg & Loomis (2000), Guermandi et al. (2010), and Hynes et al. (2018) presented large samples, with 682, 416 and 311 observations, respectively. In addition, these studies were applied in wide areas, covering several countries.

Table 3.5 - Studies applying the meta-analysis for ESV.

Authors	**Location**	**Ecosystem Service**	**Biome**	**R²**	**N (Samp. size)**	**Cut-off in *t*-test[1]**
Rosenberg & Loomis (2000)	United States and Canada	Outdoor activities	-	0.26	682	0.20
Bateman & Jones (2003)	British Forest – Great Britain	Recreation	Woodlands	0.71	77	0.38
Van Houtven et al. (2007)	United States	Water quality	-	0.59 - 0.61	131	0.10
Lindhjema & Navrud (2008)	Norway, Sweden and Finland	Non-use values related to biodiversity	Forests	0.81 - 0.87	72	0.20
Guermandi et al. (2010)	World	Flood protection, water quality, and water storage and supply	Wetlands	0.49- 0.46	416	0.10
Hjerpe et al. (2015)	United States	Forest and freshwater restoration	Forests and Fresh waters	0.58 - 0.60	127	0.18
Rao et al. (2015)	World coastal area	Shoreline protection	Coastal Areas	0.44 - 0.45	90	0.10
Hynes et al. (2018)	World	Recreation services	Coastal Areas	0.25 - 0.65	311	0.10

Note: [1] Values presented for the final/best model presented.

As previously exposed, the cut-off for the significance level adopted in the *t*-student test for the model variables was 20%, which eventually diminished the reliability of the models (i.e. it is common to use "cut-off points" of 0.5%, 1%, 5% or even 10%). Nevertheless, authors such as Rosenberg & Loomis (2000), Bateman & Jones (2003), Lindhjema & Navrud (2008) and Hjerpe et al. (2015) used *t*-values close to those adopted in our research. It will be demonstrated, in the next section, that the transfer errors obtained using these value functions are smaller than those obtained using other benefit transfer techniques.

3.7. Value function transfer errors and estimates

The validity of environmental benefit transfer has been the subject of a number of studies Brouwer & Spaninks (1999), Bergland et al. (2002) and Lindhjem & Navrud (2008). In all of them, the validity has been tested by stating a null hypothesis of no difference between the original study result and the benefit transfer estimate (Kristofersson & Navrud, 2005). As in those studies, in this study we seek to verify the differences between the estimated values from MA-BT with the values from the ESVD database, using the Transfer Error technique (see Section 3.2.3).

3.7.1. Transfer errors

To assess the accuracy of the estimated ES value meta-models, in order to justify their adoption in future research covering different locations with varied characteristics, we determined the transfer errors associated with Value transfer, Global meta function transfer, and Local meta function transfer (see Sectio 3.2.3.). This is done for the Provisioning, Regulating & maintenance, and Cultural ES value functions (see Table 3.6Table 3.7Table 3.8, respectively).

The ecosystem service values and transfer errors per biome related to the estimates for the Provisioning ES are presented in Table 6. Overall, it can be concluded that the transfer error is reduced when moving from Value transfer to Global meta function transfer and, in turn, that the transfer error is further reduced when moving to Local meta function transfer. Notable exception holds for *Wood*, which demonstrates the lowest transfer error when using Value transfer. This is explained by the fact that this variable was dropped from the restricted model (not significant according to the *t*-test). Also, in some cases, the transfer error increases slightly when moving from Global meta function transfer to Local meta function transfer (such as for *FrWa*, *Mari*, and *TeFo*), which is explained by the large variation of values in the ESVD database that contained studies from different countries, continents, and years, and in the case of those biomes, ranging from 1.5 to 3000.0 €/ha/year.

Table 3.6 - Comparison of values and transfer errors (TE) per biome for Provisioning ES, based on Value transfer, Global meta function transfer and Local meta function transfer (in 2015 €/ha/yr).

	Value transfer		**Global meta function transfer**		**Local meta function transfer**	
Biome[1]	**Value**	**TE (ETE1)**	**Value**	**TE (ETE2)**	**Value**	**TE (ETE3)**
CSys	1 336.0	926.2	81.9	56.7	185.7	11.4
CWet	362.7	1 228.2	30.7	103.9	66.0	10.1
CoRf	1 463.7	$7.0 * 10^6$	10.3	$5.0 * 10^4$	23.1	$1.6 * 10^4$
CuAr	2 795.2	$4.2 * 10^5$	141.7	$2.2 * 10^4$	741.8	$1.4 * 10^4$
Dser	82.5	106.2	1.5	2.0	1.5	2.0
FrWa	594.9	107.3	59.7	10.7	120.5	15.6
Gras	164.9	$4.5 * 10^4$	2.8	769.9	8.1	106.3
InWt	176.8	2 013.6	6.2	71.0	15.8	54.7
Mari	50.8	2.76	27.6	1.4	48.0	4.0
TeFo	68.1	203.2	10.8	32.1	14.3	41.0
TrFo	277.3	297.8	31.2	33.3	58.3	19.6
Wood	110.6	$1.1 * 10^6$	4.6	$2.7 * 10^6$	15.4	$6.5 * 10^6$

Note: [1] *CSys* = Coastal System; *CWet* = Coastal Wetland; *CoRf* = Coral Reef; *CuAr* = Cultivated Area; *Dser* = Desert; *FrWa* = Fresh Water; *Gras* = Grassland; *InWt* = Inland Wetland; *Mari* = Marine; *TeFo* = Temp./Bor. Forest; *TrFo* = Tropical Forest; *Wood* = Woodland.

Table 3.7 presents the ecosystem service values and transfer errors per biome associated with the estimates for the Regulating & maintenance ES. According to the analysis of the previous table, the TE is reduced when moving from Value transfer to Global meta function transfer and then moving to Local meta function transfer. In this case, the exceptions hold for *CSys* and *Wood*, which demonstrate the lowest transfer error when using Global meta function transfer. This is explained by the variation of the values presented in the ESVD database for these biomes. No transfer error is observed for *FrWa* when using value transfer, as only one observation for this biome is available in the ESVD. Finally, no value estimate and transfer error were calculated for *Dser* because there are no primary value estimates data for this biome in the ESVD.

Table 3.7 - Comparison of values and transfer errors (TE) per biome for Regulating & Maintenance ES, based on Value transfer, Global meta function transfer and Local meta function transfer (in 2015 €/ha/yr).

	Value transfer		**Global meta function transfer**		**Local meta function transfer**	
Biome[1]	**Value**	**TE (ETE1)**	**Value**	**TE (ETE2)**	**Value**	**TE (ETE3)**
CSys	941.9	7.6	258.3	1.8	1 381.8	3.8
CWet	5 088.3	267.3	430.6	22.5	943.2	12.3
CoRf	7 074.0	3189.4	383.9	173.0	1 236.6	18.6
CuAr	425.6	20.0	134.4	6.2	215.0	1.7
Dser	-	-	-	-	-	-
FrWa	-	-	-	-	29.8	0.7
Gras	111.9	1 464.9	11.7	153.3	22.2	37.2
InWt	1 660.2	1 430.5	188.8	162.6	747.4	17.6
Mari	748.3	260.8	18.0	6.2	28.7	1.4
TeFo	641.8	44.9	94.7	6.4	197.2	5.4
TrFo	135.7	111.0	16.4	13.1	48.4	9.6
Wood	199.0	117.5	17.9	10.7	41.4	25.0

Note: [1] See Table 2.6 for variable descriptions.

Finally, Table 3.8 presents the ecosystem service values and transfer errors per biome associated with the estimates for the Cultural ES. Again, it can be observed that the transfer error is reduced when moving from Value transfer to Global meta function transfer and next, to Local meta function transfer. Although there are exceptions, such as for *FrWa*, *InWt*, and *TrFo*, which presented similar TE across Global and Local meta function transfer. One prominent exception holds for *Gras*, which demonstrates the lowest transfer error when using Value transfer. This is justified because it contained only two observations for this biome in the database. No transfer error is observed for *Wood* when using value transfer, as only one observation for this biome is available in the ESVD. Finally, no value estimates and transfer errors were calculated for *CuAr* and *Dser* because there are no primary value estimates for these biomes in the ESVD.

Table 3.8 - Comparison of values and transfer errors (TE) per biome for Cultural ES, based on Value transfer, Global meta function transfer and Local meta function transfer (in 2015 €/ha/yr).

	Value transfer		**Global meta function transfer**		**Local meta function transfer**	
Biome[1]	**Value**	**TE (ETE1)**	**Value**	**TE (ETE2)**	**Value**	**TE (ETE3)**
CSys	156.9	156.3	90.6	90.0	186.9	33.7
CWet	3 099.8	119.3	152.6	5.6	267.0	5.1
CoRf	5 340.9	2 138.0	308.9	123.6	1 695.3	17.1
CuAr	-	-	-	-	-	-
Dser	-	-	-	-	-	-
FrWa	651.4	0.5	16.1	1.0	36.2	0.9
Gras	1.4	0.2	48.6	35.3	58.2	46.4
InWt	681.5	15.3	142.4	3.0	234.0	3.3
Mari	311.8	316.9	7.4	7.2	20.6	1.6
TeFo	878.8	$1.9 * 10^4$	9.1	204.8	13.2	180.5
TrFo	275.4	38.3	38.0	5.1	85.6	6.2
Wood	-	-	-	-	196.7	0.9

Note: [1] See Table 2.6 for variable descriptions.

Hence, it can be concluded that transfer errors are reduced significantly when using Global meta function transfer and, in particular, Local meta function transfer as compared to Value transfer. This is justified because value function transfers allow the analyst greater control over differences across sites, they can yield lower transfer errors than simple mean value transfers (Pearce et al., 1994). In fact, by comparison, value functions offer a greater reflection of the variability of a sample, because the study is dealing with a database with great variability. For this reason, finding a model that, for the most part, has obtained a superior result than other benefit transfers techniques, is an advance that justifies its application given the heterogeneity of the data.

Value functions should thereby draw upon common drivers of preferences reflected in economic theory, including only those variables applicable to all sites (Roebeling et al., 2016). Economic theory suggests that the benefits from environmental improvements should be determined by (Bateman et al., 2011): i) change in provision, ii) distance to the site, iii) distance to substitute sites, and iv) characteristics of the valuing individual (in particular income). That is why Local meta function transfer presents the lowest TE, for addressing these preferences and reflecting the context of each country.

3.7.2. Local value function transfer estimates

Ecosystem service value estimates per biome for Provisioning (ESV_{Prov}), Regulating & maintenance ($ESV_{Reg\&Main}$), and Cultural (ESV_{Cult}) ecosystem services, are presented in Table 3.9. Value estimates are thereby based on the restricted models presented in Table 3.4, using local value function transfer and mean values for the explanatory variables (from Table 3.3).

Table 3.9 - Estimated ES values per biome for Provisioning (ESVProv), Regulating & Maintenance (ESVReg&Main) and Cultural (ESVCult) ecosystem services, using Local meta function transfer and mean national values for the explanatory variables (in 2015 €/ha/yr).

Ecosystem Service[1]	*CSys*	*CWet*	*CoRf*	*CuAr*	*Dser*	*FrWa*	*Gras*	*InWt*	*Mari*	*TeFo*	*TrFo*	*Wood*
ESV_{Prov}	44.5	28.0	3.0	122.0	3.0	26.7	3.0	23.1	27.0	3.0	23.9	3.0
$ESV_{Reg\&Main}$	193.2	238.1	389.9	78.1	-	3.6	3.6	425.8	3.6	103.3	39.9	3.6
ESV_{Cult}	127.1	491.6	1 520.7	-	-	127.1	127.1	555.3	10.8	5.8	420.8	127.1
ESV_{Total}	364.8	757.7	1 913.6	200.1	3.0	157.4	133.7	1 004.2	41.3	112.2	484.5	133.7

Note: [1] ESV_{Prov} = Provisioning Ecosystem Values; $ESV_{Reg\&Main}$ = Regulating & Maintenance Ecosystem Values; ESV_{Cult} = Cultural Ecosystem Values; ESV_{Total} = Total Ecosystem Services Values.

The values found in Table 3.9 show great variability, with values ranging from ESV_{Total} = 3.0 €/ha/year for Desert areas to ESV_{Total} = 1 913.5 €/ha/year for Coral reefs. The biomes that provide largest total economic value are Coral reefs (*CoRf* = 1 913.6 €/ha/year), Inland wetlands (*InWt* = 1 004.2 €/ha/year) and Coastal wetlands (*CWet* = 757.7 €/ha/year). These biomes, in addition to standing out for providing a great diversity of ecosystem services, are also the smallest biomes in terms of the area around the globe and, consequently, the scarcest and, thus, most valuable. In fact, in studies that analyzed ES globally, such as Costanza et al. (1997), de Groot et al. (2012) and Costanza et al. (2014), these biomes were also those with the highest value.

Provisioning services represent the lowest values and are related to the supplies of products (such as food, materials, or water) with values close to their direct use values (de Groot et al., 2012). The largest provisioning ES values are provided by Cultivated areas (*CuAr* = 121.9 €/ha/year) and Coastal System (*CSys* = 44.5 €/ha/year). The lowest values were found for Coral reefs, Desert, Grasslands, and Temp./Bor. forests (*CoRf, Dser, Gras,* and *TeFo*, with a value of 3.0 €/ha/year each).

Regulating & maintenance services are linked to more indirect benefits, which are related to quality, moderation, and prevention in environmental factors (Rao et al., 2015). The largest Regulating & maintenance ES values are provided by Inland wetlands (*InWt* = 425.8 €/ha/year), followed by Coral reefs (*CoRf* = 389.9 €/ha/year) and Coastal wetlands (*CWet* = 238.1 €/ha/year), demonstrating a high added value for areas in transition, notably coastal areas. The lowest values were found for the Marine and Woodland areas (*Mari* and *Wood*, with a value of 3.6 €/ha/year each).

Cultural services represent largest values, because they involve complex issues such as aesthetics, generated inspiration, spirituality, which can be considered incommensurable values as the perception about the environment varies from person to person (de Groot et al. 2012; Hynes et al. 2018). The largest cultural ES values are Coral Reef (*CoRf* = 1 520.7 €/ha/year), Inland Wetlands (*InWt* = 555.3 €/ha/year) and Coastal Wetlands (*CSys* = 491.6 €/ha/year), while the lowest values were found for Marine areas (*Mari* = 10.8 €/ha/year) and Temp./Bor. Forest (*TeFo* = 5.8 €/ha/year).

It is necessary to be cautious when valuing ecosystem services since, although the aim of pricing is to use values in monetary units, they serve as a tool to provide better insight into the economic benefits of ecosystem goods and services. We do not try to find the shortcomings and limitations of monetary valuation, both in relation to ecosystem services and man-made goods and services (de Groot et al., 2012; Thompson et al., 2008).

When ESV's models are created and values for biomes are estimated, this does not mean the biomes in question should be treated as private commodities that can be traded in private markets. Most of those ecosystem services are public goods or the product of common assets that cannot, or should not, be sold. Although the flowers, fruits, wood, and leaves enter the market as private goods, the ecosystems that produce them, as for example forests and woodlands, are common assets. Their values are an estimation of the benefits to society expressed in a way that communicates with a broad audience. This can help to raise awareness of the importance of ecosystem services to society and serve as a powerful and essential communication tool to inform better, more balanced decisions regarding trade-offs with policies that enhance the gross domestic product but damage ecosystem services (Costanza et al., 2014).

3.8. Conclusions and Recommendations

Ecosystem service value (ESV) meta-models were designed to provide access to values in monetary units for ecosystem services (ES), taking into account the local context of the country and area under analysis. Through their application, it is possible to estimate values for 3 different types of ecosystem services (Provisioning; Regulating & maintenance; Cultural) and 12 different types of land covers (Coastal systems; Coastal wetlands; Coral reefs; Cultivated areas; Desert; Fresh water; Grasslands; Inland wetlands; Open ocean; Temperate/Boreal forests; Tropical forests; Woodlands) in the world. To this end, we built on the review and meta-analysis of the Ecosystem Service Valuation Database (ESVD).

The highest ES values were those associated with Cultural services, followed by Regulating & maintenance and, finally, Provisioning services. Among the biomes with greater associated ecosystem service values are Coral reefs, Inland wetlands, and Coastal wetlands that, among other characteristics, are transitional, aquatic-terrestrial biomes that are scarce and provide a great diversity of services.

It was observed that local independent variables, such as income, population, agricultural and forest area, and those related to the level of environmental protection, are significant explanatory variables and, thus, comprise the ESV meta-models. The application of the meta-functions provides values with greater accuracy as compared to simple value transfer and, as shown by the transfer error analysis, the application of local variables (local meta function transfer) further increases this precision.

A meta-analysis, thus, reduces value transfer errors by taking into account local specifications to determine ESV’s. There are several studies that have used meta-models for the valuation of specific ecosystem services and biomes (e.g. Van Houtven et al., 2009; Hjerpe et al., 2015; Ghermandi et al., 2010; Hynes et al., 2018). , however, we have not found such a comprehensive study in the literature that has determined the value of 3 ecosystem services for 12 different biomes in the world. Even considering that there are certain transfer errors with the application of meta-models, as compared to other benefit transfer techniques (such as value transfer and value function transfer) the meta-analysis technique has shown to be the best way to estimate the value of ecosystem services.

Some caveats to this study remain. First, there are improvements that can be made to the results, such as updating the database, adopting other explanatory variables, or even different functional forms. Second, the adoption of the ESVD, which although very broad, has some limitations, such as the necessity for further studies for biomes such as Fresh water, which presented only one study for Regulating & maintenance ES, and Woodland, which presented only one study for Cultural ES. Moreover, biomes such as Cultivated areas, Desert, and Marine presented few valuation studies, which could directly influence their estimated ES values. Third, ecosystem services and values from marine biomes face particular challenges as these are scarcely studied and poorly understood (e.g. Townsend et al., 2018; Austen et al., 2019).

Finally, it was not possible to estimate values for urban areas, albeit they are important because they have a constant relationship with human well-being through services provided by areas such as parks, squares, and green spaces, as there were no studies analyzing this land cover in the ESVD database.

We expect this study to be a step further in studies that involve valuing ecosystem services and provide a basis for future research. Not in the least because ecosystem services and values are increasingly considered in environmental planning and nature conservation. Using reliable ecosystem service value estimates from local value functions for 3 ecosystem service types across 12 biomes will facilitate this process—in particular in data-poor circumstances.

CHAPTER 4

4. ECOSYSTEM SERVICES VALUES AND CHANGES ACROSS THE ATLANTIC COASTAL ZONE: CONSIDERATIONS AND IMPLICATIONS*

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ABSTRACT

The mapping and assessment of ecosystem services supplied by Atlantic coastal zone biomes provide a highly valuable source of information for understanding their current and potential benefits to society. The main objective of this research is to map and assess the values provided by Provisioning, Regulating & maintenance and Cultural ecosystem services on the Atlantic coastal zone over the period 2005-2015. Global ecosystem service value (ESV) functions were applied to a 100 km coastal zone of countries on the Atlantic coastal zone, using land use and socio-economic data for 2005, 2010 and 2015. Results show that total Cultural ecosystem service values (ESV_{Cult}) are largest along the Atlantic coastal zone (50% of ESV_{Total}), that Tropical Forest is the biome that provides the largest total ecosystem service value (33% of ESV_{Total}) and that Latin America & Caribbean is the Atlantic coastal zone with highest ecosystem service values (55% of ESV_{Total}). Results also show a decrease in natural areas, mainly due to the increase in urban areas along the Atlantic coastal zone. Despite this process, there is an increase in unit ecosystem service values over time (+21%) due to an increase in income (+13%) and population (+15%) over the period 2005-2015. These trends in ESV over the years deserve careful attention by policy makers. A decrease in the supply of (due to land use conversion) and the increase in demand for (due to income and population growth) ecosystem services could, potentially, lead to jeopardizing ecosystem services over time.

4.1. Introduction

Coastal zones are among the most important regions for humanity. More than 30% of the world population live in coastal communities – which are twice as densely populated as inland areas (MEA, 2003; Barbier et. al., 2008; Rao et al., 2015) – and nearly 2.4 billion people (about 40% of the world population) live within 100 km (60 miles) of the coast (Burke et al., 2001). Out of the 33 world megacities, 21 are found on the coast (Martinez et al., 2007) and their resident population directly benefits from as well as impacts on the environment and coastal ecosystems. There are numerous interactions between coastal communities and natural ecosystems, and it is increasingly recognized that natural ecosystems play a crucial role in determining human wellbeing (TEEB, 2010).

Coastal areas are diverse, highly productive, ecologically important on the global scale and highly valuable for the wide range of ecosystem services (ES) they supply to human beings (e.g. de Groot et al. 2012, IPCC, 2013, IPBES. 2019). The ecosystem service types include (1) Provisioning services, such as supply of food, fuel wood, energy resources and natural products; (2) Regulating & maintenance services, such as shoreline stabilization, nutrient regulation, carbon sequestration, detoxification of polluted waters and waste disposal; and (3) Cultural services, such as tourism, recreation, aesthetics, spiritual experience, and religious and traditional knowledge (TEEB, 2010; Gundersen et al., 2016). These ES and associated values are of inestimable importance to life and human wellbeing, both to communities living in coastal zones as well as to national economies and global trade. However, they are highly vulnerable to anthropogenic pressures such as climate change impacts, sea level rise, erosion and storm events as well as being subject to population growth and economic development pressures (Roebeling et al., 2013).

Historically, in the late 1990s and early 2000s, the concept of ES slowly found its way into the policy arena, namely through the “Ecosystem Approach” and the Global Biodiversity Assessment (de Groot et al., 2012). In 2005, the concept of ES got wider interest after the publication of the Millennium Ecosystem Assessment (MEA) by the United Nations (Costanza et al., 2014). Numerous projects and groups are currently working towards better understanding, modeling, valuing and managing ES and natural capital (Costanza et al., 2014).

In the scientific arena, an increasing number of scientific publications seeks to assign monetary values to ES at different spatial scales, from local to global (Costanza et al., 1997; de Groot et al., 2012; Ghermandi & Nunes, 2013; Costanza et al., 2014). These types of contributions look at the value of a wide range of ES with a variety of methods and aim at reducing the shortcomings associated with the recurrent unavailability and, hence, exclusion of nature's values from policy and decision-making.

An important way to investigate the human dependence on coastal ES is to examine their estimated values, paying attention to their evolution over time. Generating estimates of their value can help informing policymakers by providing them insights about the costs and benefits of their actions when managing and developing coastal areas. Also, this type of analysis can be used to support policy decisions, especially under data poor situations (Rao et al., 2015).

Monetary valuation advocates for a more efficient use of limited resources and helps in deciding where protection and restoration are economically more efficient and can be delivered at least cost (Crossman & Bryan, 2009; Crossman et al., 2011). The outcomes of ES valuation studies can support coastal management decisions and conservation policies through, e.g., the establishment of compensation schemes (Payne & Sand, 2011), estimation of payments for environmental services (Salzman et al., 2018) and assessment of rates for the use of an ecosystem based on costs of ecosystem degradation (Lopes & Villasante, 2018). Even considering the limitations of the monetary valuation of ES (Kenter et al, 2021), it is far better to work with rough and ready figures than to ignore large amounts of natural capital goods by pretending they do not exist (Dasgupta, 2021).

The first step in estimating ES values is to develop a biophysical assessment of their availability that, more than determining their overall provision or accessibility, focusses on their actual use and benefit by humans (Rao et al., 2015). However, this exercise proves to be extremely difficult for many reasons. While some ES are inherently spatial, easier to evaluate and more directly measurable than others, assessments need to rely on mapping or modeling of their flow in space and time (TEEB, 2010). The fact that biophysical assessments depend on the status of scientific knowledge and data availability, pushes several authors to rely on proxies to identify service provision, as opposed to benefits, especially in cases where there is lack of consensus on the best or ideal measurement units for these ES. Thus, finding a common metric is crucial -and also challenging- to inform policy decisions. That is why monetary valuation, even in the absence of biophysical assessments, becomes a common language and framework in which the available information can be analyzed, and trade-offs can be evaluated (Rao et al., 2015).

Although the results of ES valuation studies are increasingly applied, non-market valuations typically have a limited geographical scope and are also dependent on socio-economic and cultural contexts. By using results from earlier empirical studies and applying their conclusions to new policy sites, different from that of the original study, benefit transfer arises as an attractive possibility that helps dealing with time and budget constraints whenever reliable primary valuations are unavailable (Ghermandi & Nunes, 2013; Florax et al., 2002; Nijkamp et al., 2008). However, local characteristics, such as ES location, accessibility, quality, territorial extension and socio-cultural dimensions, are crucial factors when estimating the ES value (Outeiro et al. 2015; Lopes & Villasante, 2018). Thus, the value transfer technique is particularly troublesome when study and policy sites are in different geographic and socio-economic contexts (Schmidt et al., 2016). However, the value function transfer technique, in particular when based on meta-analysis (MA), arises as an alternative to the value transfer technique as it considers phenomenon-intrinsic and context-specific factors, such as the methods and variables used in the primary valuation study (Florax et al., 2002).

Previous MA have derived value functions for specific coastal biomes and ES types, including coral reefs (Brander et al., 2007), aquatic systems (Van Houtven et al., 2007), recreational services of coastal ecosystems (Ghermandi & Nunes, 2013) or shoreline protection values of mangroves, coral reefs and wetlands (Rao et al., 2015). Albeit including a wide range of observations, these studies are limited to analyzing only one or few biomes and/or ecosystem service types systems (Van Houtven et al., 2007; Ghermandi et al. 2010; Rao et al., 2015). Hence, there is a need to assess the full range of coastal biomes and ecosystem service types to allow policy makers to consider coastal ES and values in their coastal management decisions, development strategies and conservation policies. Also, there is a lack of comprehensive studies covering the whole Atlantic coast.

Therefore, the objective of this study is to map and assess the values for 12 biomes and three different types of ecosystem service types (Provisioning; Regulating & maintenance; Cultural) for a coastal zone of 100 km of all the 63 countries that, together, form the Atlantic coastal zone, over the period 2005-2015. To this end, global value functions for a wide range of coastal biomes and ES value types are used and applied to countries on the Atlantic coastal zone, using land use and socio-economic data for 2005, 2010 and 2015. Hence, evolutions and transformations of ecosystem services values on the Atlantic coastal zone are mapped, assessed and considered. Finally, results are discussed and reflected upon, and the relevance for coastal management and policy makers is emphasized.

4.2. Materials and methods

The approach adopted in this study integrates global ecosystem service value functions (derived by Magalhães Filho et al., 2021) (see Section 4.2.1) and historical land use and socio-economic data for countries on the Atlantic coastal zone (see Section 4.2.2), to understand changes in land use, income and population (Section 4.3.1) that underpin changes in unit ecosystem service values (Section 4.3.2) and that are used to estimate changes in total ecosystem service values (Section 4.3.3) for countries on the Atlantic coastal zone for 2005, 2010 and 2015 (see Figure 4.1).

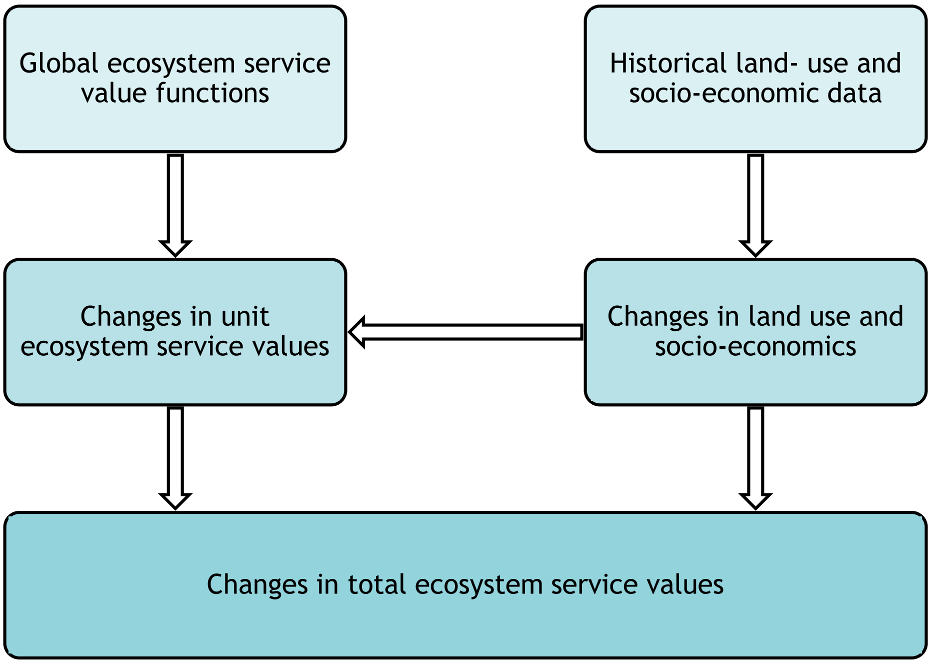

Figure 4.1 - Schematic overview of the methodology.

4.2.1. Global value functions for ecosystem services valuation

Global ecosystem service value functions from Magalhães Filho et al. (2021), are used to estimate Provisioning, Regulating & maintenance and Cultural ecosystem service values for countries on the Atlantic coastal zone. In their study, use the Ecosystem Service Valuation Database (ESVD. 2020) to estimate meta-regression functions for Provisioning, Regulating & maintenance, and Cultural ecosystem services based on, respectively, 302, 225 and 109 value estimates. Provisioning services include food, raw materials, fibers, energy and water, and are mainly based on direct market pricing, production function and group valuation studies. Regulating & maintenance services include climate regulation, erosion control, environmental regulation, genepool maintenance and pollination, and are mainly based on avoided cost, mitigation/restoration cost and payment for ecosystem services studies. Finally, Cultural ecosystem services include recreation, aesthetics, spiritual, inspirational and cognitive, and are mainly based on travel cost, hedonic pricing and contingent valuation studies. Using transfer error analysis, they show that the application of the meta-regression functions provides values with greater accuracy as compared to simple value transfer – in particular when applying local independent variable values.

Primary valuation data from the Ecosystem Service Valuation Database (ESVD. 2020) were used in combination with additional explanatory variables such as income, population density and protection status (from FAOSTAT. 2020; World Bank. 2020). Table 4.1 lists and describes the main variables used in their meta-analysis.

Table 4.1 - Meta-analysis (MA) variables description and sources (Magalhães Filho et al., 2021).

Variables	**Description**	**Data Source**
APer	Agricultural land refers to the share of land area that is arable, under permanent crops, and under permanent pastures, by percentage of land area.	FAOSTAT (2020)
FPer	Forest area with natural or planted stands of trees of at least 5 meters in situ, by percentage of land area.	
MProt	Percentage of marine protected areas, from territorial waters of a country.	World Bank (2020)
TProt	Percentage of terrestrial areas totally or partially protected, designated by national authorities.	
GNI	Gross National Income per capita, using purchasing power parity rates.	
PDen	Population density is the midyear population divided by land area in square kilometers.	
	Dummies	
CSys; CWet; CoRf; CuAr; Dser; FrWa; Gras; InWt; Mari; TeFo; TrFo; Wood	**Biomes:** Coastal System; Coastal Wetland; Coral Reef; Cultivated Area; Desert/Snow; Fresh Water; Grassland; Inland Wetland; Marine; Temp./Bor. Forest; Tropical Forest; Woodland.	ESVD (2020)
Euro; Asia; Ocea; LaAm; NoAm; Afri	**Continents:** Europe; Asia; Oceania; Latin America & Caribbean; North America; Africa.	
FProt; PProt; NProt	**Protection Status:** Fully Protected; Partially Protected; Not Protected.	

Magalhães Filho et al. (2021) use a semi-log functional form specification for the ES value functions, which implies that the marginal effect of a change in ESV depends on income and population density (Van Houtven et al., 2007, Hynes et al., 2013). The Provisioning (ESV_{Prov}), Regulating & maintenance ($ESV_{Reg\&main}$) and Cultural (ESV_{Cult}) ecosystem service value functions are determined by the type of biome (D_{Biome}), location of the continent ($D_{Continent}$), level of protection in study area (*FProt*; *MProt*; *NProt*; (CEPAL, 2020), the terrestrial (*TProt*) and marine (*MProt*) protected area (Mach et al. 2015), the percentage of agricultural (*APer*) and forest (*FPer*) land (Maes et al., 2018), population density (*PDen*) (Bateman et al., 2006) and/or income (*GNI*) (CEPAL, 2020), Resulting regression coefficient estimates, as used in the current study, are summarized in Table 4.2.

Table 4.2 - Meta-regression model specification for ecosystem services[1] (Magalhães Filho et al., 2021).

Explanatory variables[2]	ESV_{Prov}		$ESV_{Reg\&main}$		ESV_{Cult}	
	Coef.	*t-Test (sig.)*	*Coef.*	*t-Test (sig.)*	*Coef.*	*t-Test (sig.)*
CONSTANT	-6.41	0.01	-3.46	0.19	-7.37	0.03
CSys	2.68	0.01	3.98	0.01	-	-
CWet	2.22	0.01	4.19	0.01	1.35	0.20
CoRf	-	-	4.68	0.01	2.48	0.01
CuAr	3.69	0.01	3.07	0.01		
Dser	-	-				
FrWa	2.17	0.19	-	-	-	-
Gras[3]	-	-	-	-	-	-
IWet	2.03	0.01	4.77	0.01	1.48	0.20
Mari	2.18	0.15	-	-	-2.47	0.12
TeFo	-	-	3.35	0.01	-3.09	0.01
TrFo	2.06	0.01	2.4	0.01	1.2	0.20
Wood	-	-	-	-	-	-
FProt	-	-	-1.73	0.01	-	-
PProt	-	-	-	-	1.17	0.05
NProt[3]	-	-	-	-	-	-
Euro[3]	-	-	-	-	-	-
Asia	-	-	-	-	-1.75	0.06
Ocea	-	-	-	-	-1.33	0.16
LaAm	1.76	0.01	-	-	1.33	0.18
NoAm	-	-	-	-	-	-
Afri	-	-	-2.12	0.01	-	-
Aper	-0.04	0.01	-	-	-	-
FPer	-	-	-0.02	0.05	-	-
MProt	-	-	-0.02	0.19	-0.05	0.01
TProt	-0.05	0.10	-0.05	0.06	-	-
ln_GNI	0.87	0.01	0.49	0.03	1.04	0.01
ln_PDen	0.59	0.01	0.66	0.01	0.48	0.09
N	302		225		109	
R^2	0.19		0.46		0.38	

Notes: Dependent variable is ln_ESV_i

[1] ESV_{Prov} = Provisioning ecosystem service values; $ESV_{Reg\&main}$ = Regulating & maintenance ecosystem service values; ESV_{Cult} = Cultural ecosystem service values.

[2] See Table 4.1 for variable descriptions. [3] Variables used as the basis for analysis of the dummies.

4.2.2. Study area delimitation, mapping and data

The focus of this study is the whole of countries (or part of countries) on the Atlantic coastal zone. The coastal zone is that "*part of land most affected by its proximity to the sea, and that part of the ocean most affected by its proximity to the land*" (Sorensen & McCreary, 1990, p.5). Coastal zone has been defined as being located within 100 km of the coastline (following Burke et al., 2001; Small & Nicholls, 2003; Martinez et al., 2007), where the coastal zone is defined as being located within 100 km of the coastline. It is argued that this definition allows to cover most interactions between aquatic and terrestrial ecosystems that may occur on the coastal zone.

To proceed with the mapping of the Atlantic coastal zone, we base our calculations on the delimited area within 100 km of the coastline, covering 63 countries (see Figure 4.2). Small countries with a coastal area less than 10 ha were not considered in the analysis, Greenland was adopted as a country (part of the North American continent), and the islands located in Central America were united to form the Caribbean small states region. The Table 4.3 provides a list of countries in the analysis as well as the corresponding explanatory variable values applied in the value functions.

Table 4.3 - Changes in variables applied in the Meta-regression model per country.

Country/ Variables^1		**APer (%)**			**Fper (%)**			**MProt**	**TProt**	**GNI (€/2015)**			**PDen (People/Km^2)**		
Year		**05**	**10**	**15**	**05**	**10**	**15**	**(%)**	**(%)**	**05**	**10**	**15**	**05**	**10**	**15**
Angola		46	47	47	47	47	46	0	7	4,515.7	5,817.9	6,439.8	16	19	22
Benin		31	31	33	43	40	38	0	29	1,729.6	1,804.7	1,970.8	71	82	94
Cameroon		19	21	22	44	42	40	3	11	2,704.1	2,847.7	3,178.2	38	43	49
Cape Verde		19	19	20	21	21	22	0	3	5,490.7	5,679.7	5,782.0	115	122	130
Congo, D. Rep.		11	11	12	69	68	67	0	13	572.1	634.3	749.0	24	28	34
Congo, Rep.		31	31	31	66	66	65	3	41	2,975.0	4,050.7	7,631.2	11	13	14
Equatorial Guinea	Africa	12	10	10	60	58	56	0	19	21,113.5	21,715.6	23,455.9	27	34	42
Gabon		20	20	20	85	85	89	1	20	16,335.1	13,960.1	16,335.7	5	6	8
Gambia		52	61	60	47	47	48	0	4	1,389.7	1,389.7	1,389.7	153	177	206
Ghana		66	69	69	40	40	41	0	15	2,446.4	2,976.5	3,735.4	96	109	122
Guinea		57	58	59	27	27	26	1	31	1,468.9	1,558.6	1,805.0	37	41	47
Guinea-Bissau		57	58	58	74	72	70	10	17	1,346.8	1,424.3	1,513.3	48	54	62
Ivory Coast		64	65	65	33	33	33	0	23	2,270.3	2,572.9	3,126.5	58	65	73
Liberia		27	28	28	47	45	43	0	2	889.4	1,019.6	1,137.4	33	40	46
Mauritania		38	39	39	0	0	0	4	1	3,221.0	3,397.5	3,622.4	3	3	4
Morocco		67	67	69	12	13	13	0	31	5,348.5	6,365.8	7,182.8	68	72	78
Namibia		47	47	47	9	9	8	2	38	7,732.2	8,347.7	10,402.1	2	3	3

Nigeria		80	77	78	12	10	8	0	14	3,819.0	4,793.5	5,540.4	152	174	199
S. Tome and Princ.		51	51	51	58	56	56	0	29	1,920.0	2,510.0	3,080.0	164	188	208
Senegal		46	49	46	45	44	43	1	25	2,660.1	2,749.1	2,932.9	58	66	76
Sierra Leone		53	54	55	39	38	42	1	9	1,039.7	1,221.9	1,308.7	78	89	99
South Africa		80	80	80	8	8	8	12	14	10,797.7	11,722.5	12,052.4	39	42	46
Togo		60	67	70	7	5	3	0	28	1,153.4	1,259.3	1,539.4	103	118	135
Western Sahara		19	19	19	3	3	3	2	16	4,284.8	4,881.7	5,402.6	36	38	41
Belgium	Europe	46	45	44	22	23	23	37	23	40,280.6	42,384.9	41,597.5	346	360	372
Denmark		64	62	62	13	14	15	18	18	44,929.1	44,726.4	47,213.5	128	131	135
Estonia		21	22	23	53	53	51	19	20	21,972.5	21,539.2	27,001.1	32	31	30
Finland		7	8	7	73	73	73	11	15	39,284.7	40,389.4	39,472.6	17	18	18
France		54	53	52	29	30	31	26	26	37,004.6	37,674.3	38,667.8	115	119	122
Germany		49	48	48	33	33	33	45	38	38,050.8	41,235.9	45,011.6	236	235	234
Iceland		19	19	19	0	0	0	0	17	34,552.1	34,552.1	34,552.1	3	3	3
Ireland		62	66	64	10	11	11	2	14	41,953.2	37,811.0	45,483.2	60	66	68
Latvia		28	29	30	53	54	54	16	18	17,346.6	18,481.5	22,889.9	36	34	32
Lithuania		45	44	48	34	35	35	22	17	18,273.3	20,672.3	25,923.7	53	49	46
Netherlands		57	56	55	11	11	11	21	11	43,221.4	46,241.4	46,976.0	483	493	503
Norway		3	3	3	33	33	33	1	17	63,509.4	62,994.4	66,583.7	13	13	14
Poland		52	47	47	30	30	31	23	40	16,890.7	20,985.8	24,368.7	125	124	124
Portugal		42	40	40	36	35	35	8	23	26,181.9	26,317.7	25,859.7	115	115	113
Russia		13	13	13	49	50	50	3	10	19,086.2	22,646.9	24,032.3	9	9	9
Spain		58	55	53	35	36	37	9	28	32,421.9	32,045.4	32,264.7	87	93	93
Sweden		8	8	7	69	68	69	8	14	41,835.8	44,175.5	46,167.5	22	23	24
United Kingdom		70	71	71	12	13	13	20	28	37,682.1	36,534.4	38,116.0	250	259	269
Canada	No Am.	7	7	7	38	38	38	1	10	39,812.5	39,994.0	42,585.1	4	4	4
Greenland		1	1	1	0	0	0	5	41	44,929.1	44,726.4	47,213.5	0	0	0
Mexico		55	55	55	35	34	34	2	14	15,813.7	15,970.5	17,074.2	55	59	63
United States		45	45	44	33	34	34	41	13	49,979.8	50,296.8	54,039.3	32	34	35
Argentina	Latin Am. and	50	54	54	11	10	10	4	9	13,885.8	18,278.7	18,900.8	14	15	16
Brazil		33	33	34	61	60	59	2	29	12,007.0	14,194.3	14,490.3	22	23	24
Chile		21	21	21	22	22	24	13	18	15,610.7	17,989.2	21,653.5	22	23	24
Colombia		38	38	40	54	53	53	2	14	9,130.6	10,567.2	12,951.0	38	41	43
Falk Island		93	91	92	0	0	0	20	28	13,138.8	13,138.8	13,138.8	0	0	0
French Guinea		0	0	0	99	99	99	26	26	7,250.0	9,790.0	11,470.0	2	2	2
Guyana		9	9	9	84	84	84	0	9	4,110.0	5,670.0	7,510.0	4	4	4
Suriname		0	1	1	99	98	98	2	15	10,390.0	13,910.0	15,430.0	3	3	4
Uruguay		85	82	83	9	10	11	1	4	12,638.1	16,521.0	19,036.2	19	19	19
Venezuela		24	24	24	54	54	53	3	54	15,010.3	16,783.1	16,763.1	30	32	34
Belize		7	7	7	62	61	60	10	38	7,054.1	7,108.7	7,523.2	12	14	16

Caribbean islands	C	52	52	51	28	30	32	1	14	11,538.8	13,724.4	15,494.1	17	17	18
Costa Rica	a	35	36	35	49	51	54	1	28	10,520.1	12,484.7	13,951.7	84	90	95
Guatemala	r	43	37	36	37	35	33	1	32	6,159.5	6,537.0	7,127.7	122	137	152
Honduras	i	28	29	29	52	46	41	4	28	3,480.1	3,731.3	3,955.4	67	74	81
Nicaragua	b	44	42	42	29	26	26	3	37	3,631.3	3,855.4	4,708.6	45	48	52
Panama	.	30	30	30	64	63	62	2	21	11,199.8	14,181.7	18,635.5	45	49	53

Note: [1] See Table 4.1 for variable descriptions.

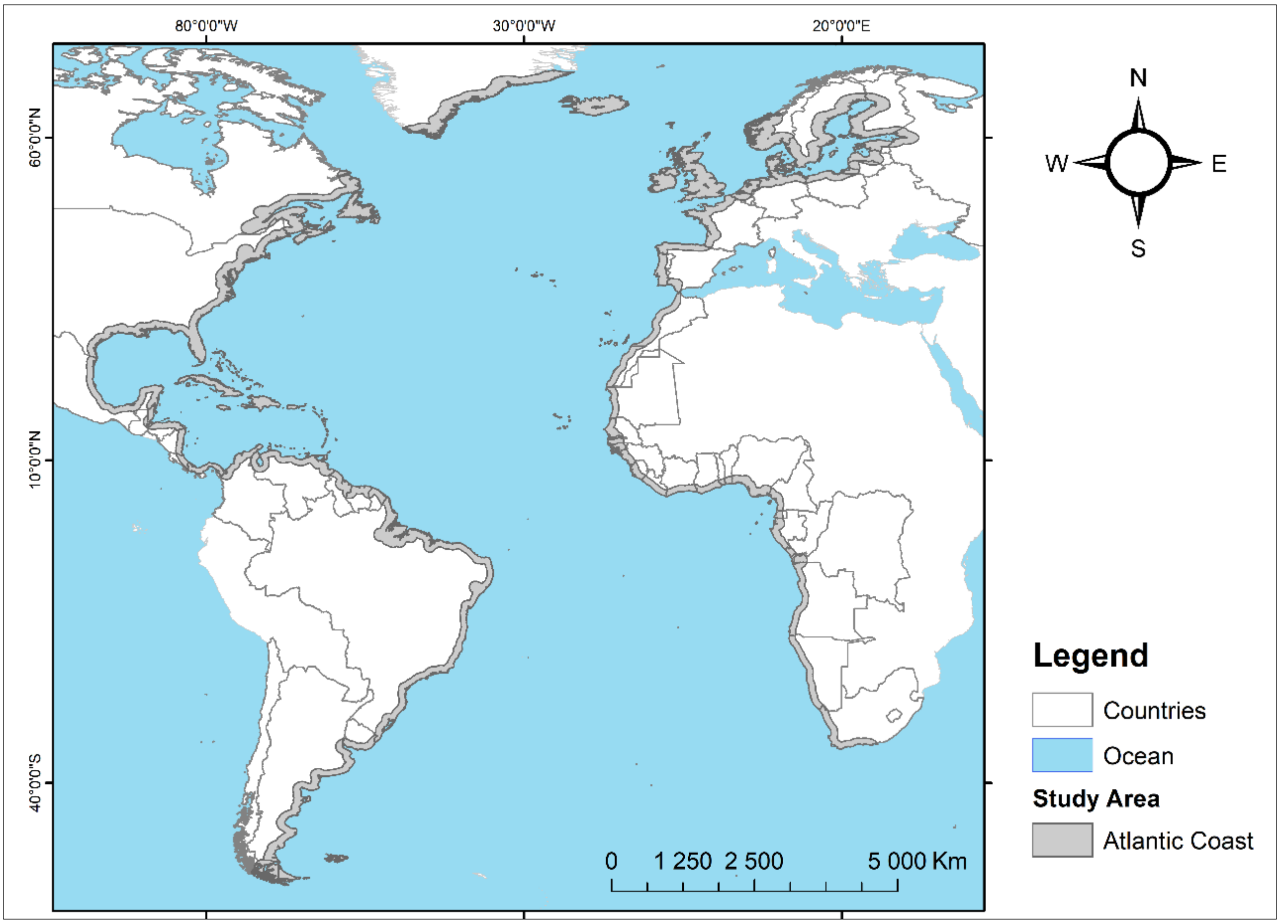

Figure 4.2 - Study Area: Atlantic coastal zone.

In turn we build a historical land use database in order to obtain values and trends over time. We use data from the Climate Change Initiative - Land Cover (CCI-LC)[1], available from the European Space Agency (ESA Climate Change Initiative, 2020). From CCI-LC we use the land use information for the years 2005, 2010 and 2015 and, using GIS tools, extract information related to the Atlantic coastal zone. As the CCI-LC land use typology

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[1] The CCI-LC project delivers consistent global land use data at 300.00 m spatial resolution on an annual basis from 1992 to 2015 for the whole world. The Coordinate Reference System (CRS) used for the global land cover databases is a geographic coordinate system (GCS) based on the World Geodetic System 84 (WGS84) reference ellipsoid.

is different from that chosen in this study, we perform a reclassification of land cover according to the biomes used in the value functions. This results in the following land uses: Coastal System, Coastal Wetland, Cultivated Area, Desert/Snow, Fresh water, Grassland, Inland Wetland, Temperate/Boreal Forest, Tropical Forest, Woodland and Urban Areas (see Table 4.4). Explanatory variable values for agricultural land as a percentage of land area (*APer*) and forest area as a percentage of land area (*FPer*), are obtained from FAOSTAT (2020). The marine protected areas as a percentage of national territorial waters (*MProt*) and the terrestrial protected areas as a percentage of national terrestrial area (*TProt*), are obtained from the World Bank (2020).

Table 4.4 - Land cover reclassification.

Biome		**Land cover (CCI-LC land use typology)**
CSys	Coastal System	Bare (Un/Consolidated) Areas in Europe, Latin America & Caribbean, North America
CWet	Coastal Wetland	Tree cover, flooded, saline water and Shrub or herbaceous cover, flooded, fresh/saline/brakish water
CuAr	Cultivated Area	Cropland, rainfed; Herbaceous cover; Tree or shrub cover
Dser	Desert/Snow	Permanent snow and ice and; Bare (Un/Consolidated) Areas in Africa
FrWa	Fresh Water	Water bodies
Gras	Grassland	Grassland; Sparse vegetation; Sparse tree; Sparse shrub and; Sparse herbaceous cover.
InWt	Inland Wetland	Tree cover, flooded, fresh or brakish water
TeFo	Temp./Bor. Forest	Tree cover, broadleaved, needleleaved and mixed leaf type, evergreen and deciduous in the northern hemisphere
TrFo	Tropical Forest	Tree cover, broadleaved, needleleaved and mixed leaf type, evergreen and deciduous in the southern hemisphere
Wood	Woodland	Mosaic natural vegetation (tree, shrub, herbaceous cover) with cropland or shrubland (<50%)
UrbA	Urban Area	Urban areas

Finally, we build a historical income and population database for gross national income (*GNI*) and population density (*PDen*) per country. To this end, we use data from the World Bank (2020) (see Table 4.3).

4.3. Results

4.3.1. Land-use and socioeconomic changes in Atlantic coastal zone

When conducting ES value analysis, it is crucial to understand the land-use and socio-economic dynamics, not only to provide a diagnosis of the study area but, in particular, to understand the land use, income and population evolution over time that underpin changes in unit (Section 4.3.2) and total (Section 4.3.3) ES values. We divided our analysis by continents (Africa, Europe, Latin America & Caribbean and North America) and calculate their total area by biome, for each year. Table 4.5 presents the area (in 10^3 ha) for each biome, in 2005.

The Atlantic coastal zone has great diversity of biomes, with predominance of natural (<80%) over anthropic (>20%) areas. In general, the main biomes are Tropical Forest (*TrFo*) in the Southern Hemisphere, Temperate or Boreal Forest (*TeFo*) in the Northern Hemisphere and Cultivated Area (*CuAr*), which represent more than 50% of the Atlantic coastal zone. Other natural biomes are Woodlands (*Wood*) and Grassland (*Gras*) that, although occupying a smaller area, represent a large percentage of the total area. However, each continent has its own characteristics. Table 4.5 shows that the most significant land use type is Cultivated Area (*CuAr*) on the African coastal zone, and Temp./Bor. Forest (*TeFo*) and Tropical Forest (*TrFO*) in the European, Latin American & Caribbean and North American coastal zones. The less important – generally declining – land use types are Inland Wetland (*InWt*) and Coastal System (*CSys*), which represent less than 3% of the Atlantic coastal zone.

Table 4.5 - Atlantic coastal zone land use per continent for 2005 (in 10^3 ha).

Continents\ Biomes[1]	**Africa**	**Europe**	**Latin America & Caribbean**	**North America**
CSys	2,167.39	10,128.85	1,028.64	4,374.74
CWet	4,539.12	15,160.00	8,958.75	6,253.70
CuAr	51,344.05	101,166.91	58,547.82	32,272.67
Dser	44,553.33	406.81	948.22	49,599.03
FrWa	2,472.72	18,396.12	8,957.20	15,509.22
Gras	13,445.43	66,065.92	56,529.54	36,266.72
InWt	10.36	3.72	8,338.24	9,962.09
TeFo	-	134,397.52	-	144,151.06
TrFo	41,445.89	-	130,571.77	-
Wood	31,061.10	37,156.64	74,492.07	33,344.84
UrbA	1,063.48	9,049.43	2,624.50	6,782.75
Total	**192,102.86**	**391,931.92**	**350,996.76**	**338,516.82**

Note: [1] See Table 3.4

To perform an evaluation in land use transformation over the period 2005 to 2015, we examined the differences between each biome along the Atlantic coastal zone. Results, as shown in Table 4.6 (in 10^3 ha), indicate an expressive increase in Urban Area (*UrbA*) across the Atlantic coastal zone as well as a significant decrease in Forest (*TrFo* and *TeFo*) in Africa, Europe and North America. Grassland (*Gras*) also suffer a major decrease in Africa, while Cultivated Area (*CuAr*) and Fresh Water (*FrWa*) are significantly reduced in Latin America & Caribbean.

Table 4.6 - Changes in Atlantic coastal zone land use per continent over the period 2005-2015 (in 10^3 ha and %).

Continents \ Biomes[1]	**Africa**	**Europe**	**Latin America & Caribbean**	**North America**
CSys	111 (5.1%)	-18 (-0.2%)	8 (0.8%)	61 (1.4%)
CWet	-13 (-0.3%)	157 (1.1%)	48 (0.5%)	-9 (-0.2%)
CuAr	570 (1.1%)	854 (0.8%)	-1,311 (-2.2%)	-205 (-0.6%)
Dser	-8 (-0.1%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
FrWa	-33 (-1.3%)	1 (0.1%)	-96 (-1.1%)	-10 (-0.1%)
Gras	-315 (-2.4%)	229 (0.36%)	64 (0.1%)	-61 (-0.2%)
InWt	-2 (-21.9%)	0.3 (7.8%)	36 (0.4%)	-19 (-0.2%)
TeFo	-	-3,621 (-2.7%)	-	-1,392 (-1.0%)
TrFo	-588 (-1.4%)	-	368 (0.3%)	-
Wood	-95 (-0.3%)	1,770 (4.8%)	284 (0.4%)	197 (0.6%)
UrbA	373 (35.1%)	628 (6.9%)	599 (22.8%)	1,438 (21.2%)

Note: [1] See Table 3.4

Urbanization (*UrbA*) is observed at higher rates in Africa (+35.1%) followed by Latin America (+22.8%), North America (+21.2%) and Europe (+6.9%). These differences are basically due to the relatively late process of economic development and demographic growth in Africa as compared to Europe. However, in relation to area (in ha), North America presented the largest increase in Urban Area (+1.4 million ha) due to its larger absolute coastal area.

In Europe and North America, deforestation of, in particular, Temp./Bor. Forest (*TeFo*), has resulted in the transformation into different biomes. In the case of Europe, these changes were into anthropic biomes, increasing Urban Area (*UrbA*) and Cultivated Area (*CuAr*) by 1.48 million ha, and the remaining Woodland (*Wood*) by 1.8 million ha, mainly into Agroforestry areas with low diversity (predominantly pine and eucalyptus). In North America, Temp./Bor. Forest (*TeFo*) and Cultivated Area (*CuAr*) decreased by more than 1.6 million ha, resulting in the transformation of these areas into, mostly, Urban Area (*UrbA*; +1.4 million ha) and Woodland (*Wood*; +0.2 million ha).

On the African coast, there is a decrease in natural areas, especially in Tropical Forest (*TrFo*), Grassland (*Gras*) and Woodland (*Wood*), which together decreased by almost 1.0 million ha. This area has been converted into anthropic, Urban Area (*UrbA*) and Cultivated Area (*CuAr*), and a small part has been transformed into a Coastal System (*CSys*; + 111.2 thousand ha), mainly bare areas such as dunes, shrubs and cliffs. There is also a decrease in Inland Wetland (*InWt*) that, although small in area (about 2.3 thousand ha), represents a high percentage loss (-21.9%).

The Latin America & Caribbean coastal zone showed a reduction in the Cultivated Area (*CuAr*; -1.3 million ha), losing 2.2% of their area by 2015. Agricultural activities in these countries moved to more inland areas, while most of the vacated area has changed to Urban Area (*UrbA*; + 0.6 million ha), Tropical Forest (*TrFo*; +368 thousand ha), and Woodland (*Wood*; due to the use for agroforestry exploitation).

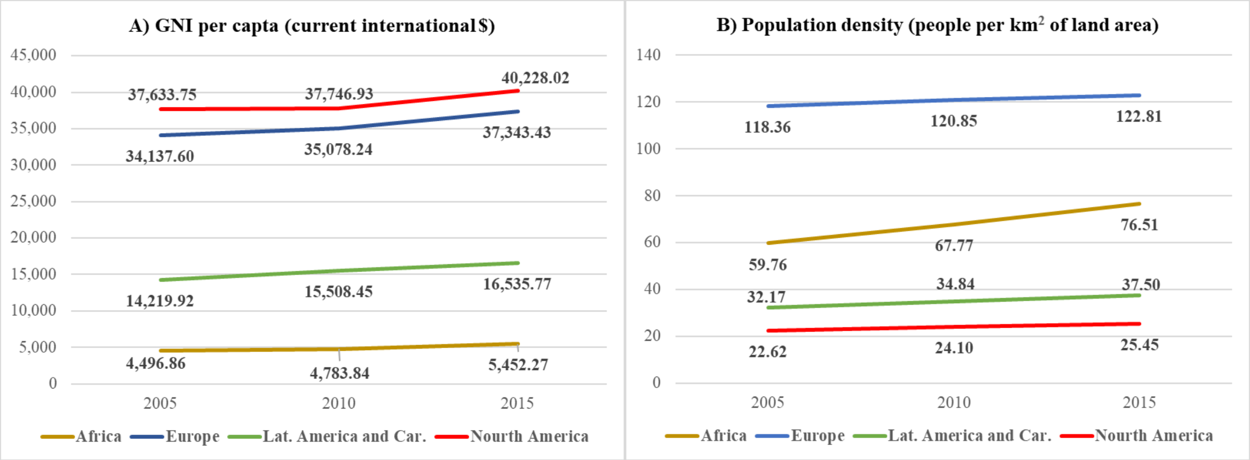

Figure 4.3 - Socio-economic indicators over the period 2005-2015: **A)** Gross National Income *per capita* (*GNI*) and **B)** Population Density (*PDen*), for continents in the Atlantic coastal zone.

Considering the socio-economic situation and changes over the period 2005-2015, information about average *GNI* and *PDen* per continent (based on specific data for the corresponding countries along the Atlantic coastal zone) are shown in Figure 4.3. *GNI* per capita (Figure 4.3.a) showed an increase in Atlantic coastal zone countries over the years. Countries located in the Northern Hemisphere, Europe and North America, present higher income (with a *GNI per capita* of \$37-40 thousand) than countries in the South, Latin America, Caribbean and Africa (which show *GNI per capita* values of below \$17 thousand). However, although *GNI* is smallest in Africa, it has been the fastest growing (more than +20.0% between 2005-2015), while in Europe and North America *GNI* growth rates were lower (+10.0% between 2005-2015).

In all considered continents, population density increased over the period 2005-2015 (Figure 4.3b). Higher *PDen* are located in the European coastal zone (120.0 inhabitants/km^2). However, the second most populated continent on the Atlantic coastal zone is Africa, followed by Latin America & Caribbean and North America occupying the last position (less than 25 inhabitants/km^2). African countries had the highest population growth rate over the concerned period, with *PDen* increasing by 28.0% between 2005-2015, while Europe it grew by less than 4.0% over the same period.

On the Atlantic coastal zone, the considered countries showed an increase in urbanization as well as income and population density over the years. There was also a decrease in natural areas, mainly in the Northern Hemisphere, with emphasis on the European coastal zone. North America has the largest *GNI* and smallest *PDen*, with a large decrease in natural areas along the Atlantic coastal zone, especially temperate forests. Understanding these issues is crucial in ES valuation which, as will be presented below, are intertwined with land use and occupation as well as socioeconomic factors.

4.3.2. Unit ecosystem service value changes on Atlantic coastal zone

Results obtained for the different unit ecosystem service values (ESV_{Prov}, $ESV_{Reg\&main}$ and ESV_{Cult}; in €/ha/year), applying the value functions and using the annual values of explanatory variables (namely GNI, PDen, MProt, TProt, APer and FPer) for the years 2005, 2010 and 2015, are presented in this section. We present the unit ESV by continent and biome as well as by country in, respectively, tables and maps, the Table 4.7 show the Changes of ESV per country.

It is shown that unit ESV tend to increase over the years, mainly due to the increase in income and population density. Each biome evaluated presents unique values, according to its location and other regional characteristics. The next subsections present a description of the unit ecosystem service values by type (Provisioning; Regulating & maintenance; Cultural).

Table 4.7 - Changes of ESV[1] per country (Value in €/ha/year, 2015 price levels).

Country/ Continent[2]		**ESV_{Prov}**			**$ESV_{Reg\&Main}$**			**ESV_{Cult}**			**ESV_{Total}**		
		5	**10**	**15**	**5**	**10**	**15**	**5**	**10**	**15**	**5**	**10**	**15**
Angola	**Afric**	13	19	23	5	6	7	22	31	37	39	55	67
Benin		33	37	44	5	6	6	4	5	6	42	48	55
Cameroon		51	60	73	3	3	4	32	35	42	86	98	118
Cape Verde		179	189	199	75	79	82	48	51	53	302	319	334
Congo. D. Rep.		19	23	30	1	1	2	2	2	3	22	27	34
Congo. Rep.		4	6	10	0	1	1	54	81	167	58	87	178
Equatorial Guinea		166	195	236	2	2	3	303	349	419	471	546	658
Gabon		36	34	43	1	1	2	98	90	115	134	125	160
Gambia		52	57	62	29	32	35	15	16	17	96	105	115
Ghana		27	35	45	14	17	21	12	16	21	54	68	87
Guinea		3	4	5	3	4	4	13	14	18	20	22	27
Guinea-Bissau		6	7	8	3	3	4	11	12	14	20	22	25
Ivory Coast		16	19	25	8	9	11	6	7	8	30	35	44
Liberia		37	47	56	6	7	9	6	7	9	49	62	74
Mauritania		1	1	2	1	1	1	2	2	2	3	4	4
Morocco		9	11	13	6	7	8	16	19	23	31	38	43
Namibia		0	0	0	0	0	0	1	2	2	2	2	2
Nigeria		23	31	37	45	55	64	58	78	96	127	164	198
S. Tome and Princ.		9	12	16	1	2	2	59	83	106	69	96	124
Senegal		24	27	31	4	5	6	14	15	17	42	47	53
Sierra Leone		22	27	30	12	14	15	7	8	9	40	49	55
South Africa		9	10	10	8	8	9	32	36	38	48	54	57
Togo		12	14	18	12	14	17	6	7	9	30	35	44
Western Sahara		5	6	6	0	0	0	0	0	0	5	6	6
Belgium	**Euro**	843	902	905	527	554	561	27	30	30	1,398	1,485	1,495
Denmark		364	367	393	695	702	736	93	94	102	1,152	1,163	1,231
Estonia		139	139	168	98	95	103	46	45	58	283	279	329
Finland		266	281	281	93	95	95	31	33	33	391	408	409
France		261	270	280	248	251	257	33	37	38	542	558	576

Germany		238	254	273	111	115	119	15	16	18	364	385	411
Iceland		33	34	35	100	105	108	61	63	64	194	202	206
Ireland		48	47	56	138	139	156	330	309	381	516	495	592
Latvia		121	126	147	42	41	44	10	11	14	173	179	206
Lithuania		176	188	219	173	176	189	15	17	21	364	380	429
Netherlands		726	777	797	1,040	1,087	1,108	140	151	155	1,906	2,015	2,060
Norway		203	212	237	192	196	208	393	400	443	788	808	887
Poland		64	77	88	71	79	85	8	10	11	143	166	184
Portugal		200	200	193	237	234	224	63	64	63	500	499	480
Russia		126	146	155	28	31	32	15	18	20	169	195	206
Spain		72	73	73	200	207	206	70	71	72	342	352	351
Sweden		261	293	322	121	127	133	31	34	37	413	454	492
United Kingdom		95	94	100	385	387	404	145	143	153	625	624	656
Canada	**NoAm**	64	67	73	87	90	95	65	68	74	216	224	242
Greenland		1	1	2	1	1	1	7	7	8	9	9	10
Mexico		74	77	85	278	294	316	81	84	93	432	455	495
United States		108	111	119	245	252	267	25	26	28	378	389	414
Argentina	**LaAm**	151	197	210	70	83	88	145	198	211	367	478	508
Brazil		174	205	213	27	30	31	1,046	1,284	1,340	1,247	1,518	1,584
Chile		293	341	412	36	40	45	234	279	347	564	660	804
Colombia		487	569	698	47	52	60	259	314	398	794	935	1,156
Falk Island		0	0	0	0	0	0	9	9	9	10	10	10
French. Guinea		78	102	117	0	0	0	30	41	49	109	143	166
Guyana		114	151	196	7	8	9	82	115	156	203	275	361
Suriname		235	313	354	2	2	2	191	266	304	427	581	660
Uruguay		83	104	118	121	139	149	388	527	623	592	769	890
Venezuela		114	130	134	17	19	19	1,380	1,621	1,662	1,511	1,770	1,816
Belize		111	119	133	6	7	8	442	468	519	559	594	659
Caribbean islands		201	237	268	45	50	54	270	330	378	516	617	700
Costa Rica		262	302	335	60	69	75	823	1,035	1,215	1,145	1,405	1,625
Guatemala		170	190	218	66	73	82	472	523	601	709	786	900
Honduras		98	110	121	7	7	8	185	208	229	290	326	358
Nicaragua		21	23	28	17	18	21	162	176	223	201	216	271
Panama		382	486	643	42	50	61	545	734	1,024	968	1,270	1,727

Note: [1] ESV_{Prov} = Provisioning Ecosystem Values; $ESV_{Reg\&Main}$ = Regulating & Maintenance Ecosystem Values; ESV_{Cult} = Cultural Ecosystem Values; ESV_{Total} = Total Ecosystem Services Values. [2]Continents: Afric = Africa; Euro = Europe; NoAm = North America; LaAm = Latin America and Caribbean.

Unit value of Provisioning services

Provisioning services are related to materials creation, such as food, water, raw materials, fibers, energy and water. The highest unit ESV_{Prov} are observed in Cultivated Area (*CuAr*), the land use type where food, fiber and wood production are most concentrated. The Latin America & Caribbean coastal zone showed the highest unit value associated with this biome, increasing from 663 to 889 €/ha/year over the period 2005-2015 (Table 4.8) due to a growth in population and income (both leading to increased demand). Other biomes with high provisioning services unit values are associated with Coastal System (*CSys*) and Inland Wetland (*InWt*), which contribute to the production of food, raw materials and water.

In general, the coastal zones with the highest unit ESV_{Prov} are in Latin America & Caribbean (values ranging between 179-239 €/ha/year), which is explained by the high natural productivity of tropical regions in combination with high population density (demand) in these coastal areas. Another continent with a high unit ESV_{Prov} is Europe (ESV_{Prov} between 191-215 €/ha/year), which is explained by the high income (willingness-to-pay) and population density (demand) in its coastal areas. The lowest unit provisioning ES values are observed in Africa (unit ESV_{Prov} between 18-26 €/ha/year), given its low income and population density.

Table 4.8 - Unit Provisioning ecosystem service values (ESV_{Prov}) per continent and biome for 2005, 2010 and 2015 (in €/ha/year, 2015 price levels).

Continents\ Biomes[1]	**Africa**			**Europe**			**Latin America & Caribbean**			**North America**		
	2005	**2010**	**2015**	**2005**	**2010**	**2015**	**2005**	**2010**	**2015**	**2005**	**2010**	**2015**
CSys	50	59	66	223	229	244	245	307	328	88	92	101
CWet	14	16	19	190	195	209	147	181	199	130	134	146
CuAr	43	51	62	599	634	672	663	806	889	472	489	533
Dser	2	2	2	44	45	49	49	57	69	1	1	1
FrWa	15	16	20	210	222	235	175	211	239	112	116	126
Gras	1	1	1	13	13	14	16	20	22	7	7	8
InWt	9	12	15	264	280	298	117	141	152	119	123	134
TeFo	-	-	-	28	29	31	-	-	-	15	15	17
TrFo	22	25	30	-	-	-	138	168	191	-	-	-
Wood	1	2	2	19	20	22	12	14	16	14	15	16
ESV_{Prov} (av.)	**18**	**21**	**26**	**191**	**203**	**215**	**179**	**215**	**239**	**66**	**68**	**74**

Note: [1] See Table 3.4.

Figure 4.4 presents the unit ESV_{Prov} (in €/ha/year) for each country on the Atlantic coastal zone, where it clearly stands out that smaller unit values (ESV_{pro} < 10 €/ha/year) are concentrated on the African coastal zone together with countries such as Greenland and Malvinas/Falkland Islands. The main reasons for these low values are the large concentration of low value-added biomes, such as Desert/Snow (*Dser*), and the low population density (demand).

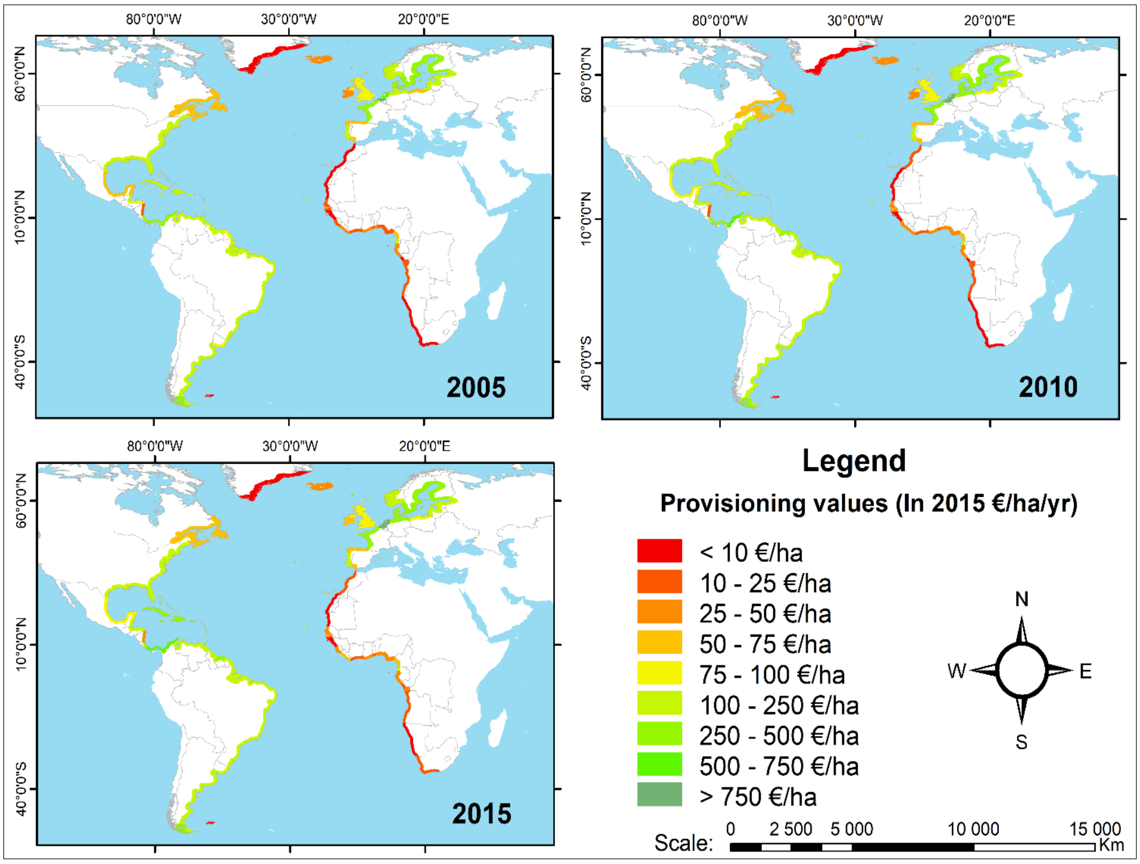

Figure 4.4 - Unit Provisioning ecosystem service values (ESV_{Prov}) per country for 2005, 2010 and 2015 (in €/ha/year, 2015 price levels).

Countries with the highest unit values (ESV_{Prov} >750 €/ha/year) are located on the European coastal zone, mainly in Belgium and Netherlands, with unit values ranging from 843-905 €/ha/year and 726-797 €/ha/year, respectively, namely due to the high percentage of coastal area that is dominated by agricultural activities (the biome with higher associated unit ESV_{prov}) in combination with the high income (willingness-to-pay) and population density (demand). The Latin American coastal zone also presents high unit values in provisioning services, especially in Colombia and Panama (ESV_{Prov} > 690 €/ha/year). This is, also, due to the high percentage of coastal area dominated by highly productive agricultural activities in combination with high population density (demand).

Unit value of Regulating & maintenance services

Regulating & maintenance services are indirectly enjoyed by humans, such as climate regulation, erosion control, environmental regulation, genepool maintenance and pollination. Results for the Atlantic coastal zone indicate that the biomes with the highest associated unit $ESV_{Reg\&main}$ are Coastal System (*CSys*), Coastal Wetland (*CWet*) and Inland Wetland (*InWt*), notably in the Northern Hemisphere (Table 4.9). These biomes, which feature the interface between aquatic and terrestrial environments, generate a series of passive benefits that are often not directly acknowledged by users and non-users (Costanza, et al, 2017). Coastal zones in the Northern Hemisphere, namely Europe and North America, host a wide range of high-value economic activities as well as densely populated cities (in particular in Europe) that benefit from these Regulating & maintenance services and, hence, unit $ESV_{Reg\&main}$ are high. On the other hand, in the Southern Hemisphere, namely Africa and Latin America & Caribbean, coastal areas mainly host lower-value agricultural activities and less densely populated cities (in particular in Latin America & Caribbean) and, thus, associated unit $ESV_{Reg\&main}$ are low.

Table 4.9 - Unit Regulating & maintenance ecosystem service values ($ESV_{Reg\&main}$) per continent and biome for 2005, 2010 and 2015 (in €/ha/year, 2015 price levels).

Continent\ Biomes[1]	**Africa**			**Europe**			**Latin America & Caribbean**			**North America**		
	2005	**2010**	**2015**	**2005**	**2010**	**2015**	**2005**	**2010**	**2015**	**2005**	**2010**	**2015**
CSys	0	0	0	348	361	375	302	355	374	110	115	122
CWet	59	70	80	752	765	798	215	252	267	596	621	661
CuAr	18	21	24	393	401	415	104	120	129	201	210	225
Dser	0	0	0	0	0	0	0	0	0	0	0	0
FrWa	1	1	1	7	7	8	3	4	4	5	5	6
Gras	1	1	1	24	24	26	6	7	7	4	4	4
InWt	53	67	75	526	546	572	158	177	185	991	1,026	1,089
TeFo	-	-	-	182	188	195	-	-	-	188	195	208
TrFo	6	7	8	-	-	-	22	25	27	-	-	-
Wood	1	1	1	14	14	15	5	6	7	7	7	7
$ESV_{Reg\&main}$ (av.)	**8**	**9**	**11**	**208**	**212**	**220**	**38**	**43**	**46**	**142**	**147**	**156**

Note: [1] See Table 3.4.

Table 4.9 and Figure 4.5 show that the European coast presents the highest $ESV_{Reg\&main}$ unit values, followed by the North American coastal region. The EU countries with the highest unit values are Netherlands, with ($ESV_{Reg\&main}$ > 1,000 €/ha/year), Denmark and Belgium, respectively ($ESV_{Reg\&main}$ > 500 €/ha/year each). Besides their high income and population density, these countries concentrate a wide range of wetlands areas (*CWet* and *InWt*) that provide large regulating & maintenance services and values. Results also show low $ESV_{Reg\&main}$ values associated with countries on the African and Latin American coastal zone (below $ESV_{Reg\&main}$ < 100 €/ha/year), with the exception of Uruguay, which presents a value of 121-149 €/ha/year over the period 2005-2015.

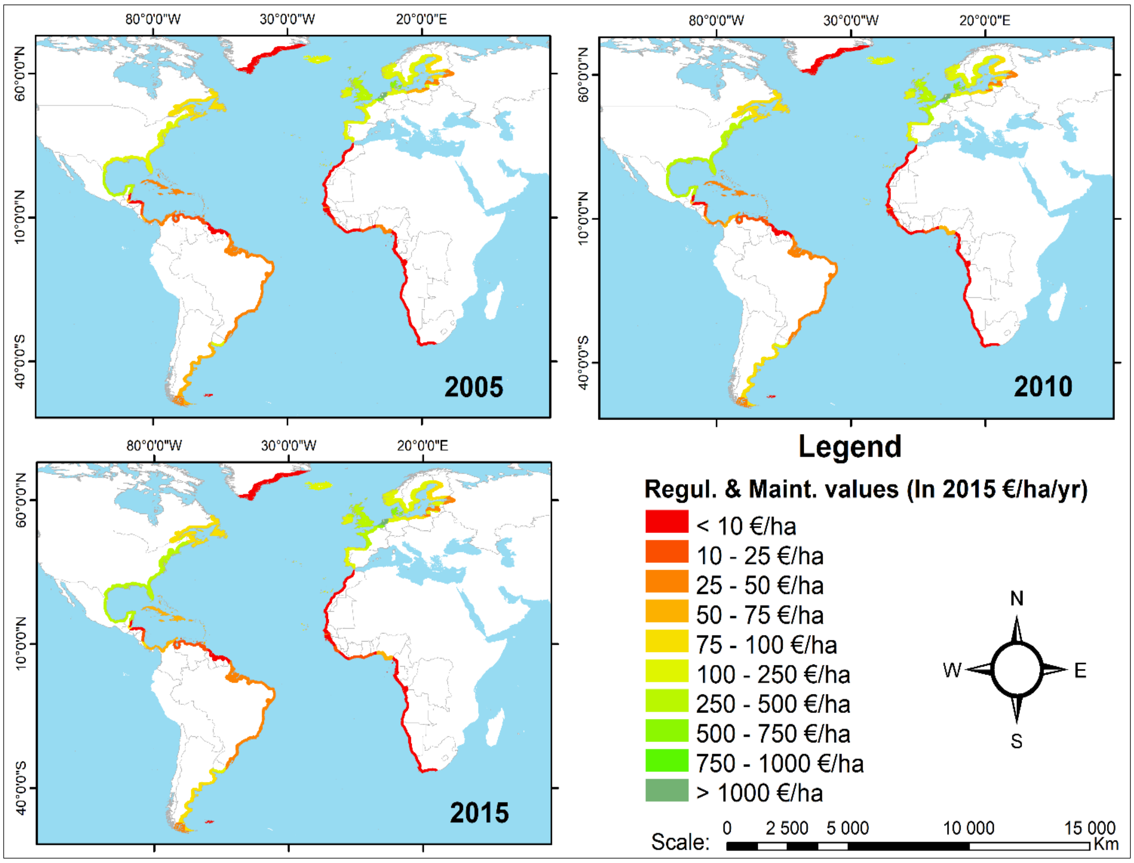

Figure 4.5 - Unit Regulating & maintenance ecosystem service values ($ESV_{Reg\&main}$) per country for 2005, 2010 and 2015 (in €/ha/year, 2015 price levels).

Unit value of Cultural services

Cultural ES reflect people's physical and mental interactions with nature and are increasingly recognized for providing non-material benefits to human societies

(Rodrigues, et al., 2017), such as recreation, aesthetics, spiritual, inspirational and cognitive. The regions that provide largest unit ESV_{Cult} are Latin America & Caribbean, well-known for their paradisiac coastal zones that constantly receive millions of tourists from all over the world. For example, in 2019, tourism accounted for 42% and 10% of total exports (goods and services) in Latin America and the Caribbean Islands, respectively. Its share exceeded 50% in some countries of the Caribbean (CEPAL, 2020). The biomes with the higher associated ESV_{Cult} are Inland Wetland (*InWt*), with values between 2.4-3.0 thousand €/ha/year, followed by Coastal Wetland (*CWet*), with values between 1.3-1.7 thousand €/ha/year, and Tropical Forest (*TrFo*), with values between 1.2-1.5 thousand €/ha/year (Table 8). The unit ESV_{Cult} values obtained for Latin America & Caribbean are much higher than those for other continental coastal areas (624-817 €/ha/year) – up to 6 times higher than in Europe, the second coastal zone with high associated cultural values.

Table 4.10 - Unit Cultural ecosystem service values (ESVCult) per continent and biome for 2005, 2010 and 2015 (in €/ha/year, 2015 price levels).

Continent\ Biomes[1]	**Africa**			**Europe**			**Latin America & Caribbean**			**North America**		
	2005	**2010**	**2015**	**2005**	**2010**	**2015**	**2005**	**2010**	**2015**	**2005**	**2010**	**2015**
CSys	19	25	29	210	214	215	360	443	463	98	101	101
CWet	81	99	121	913	914	904	1,280	1,570	1,676	284	293	293
CuAr	0	0	0	0	0	0	0	0	0	0	0	0
Dser	0	0	0	0	0	0	0	0	0	0	0	0
FrWa	22	26	33	177	183	182	341	419	452	137	141	141
Gras	21	26	31	157	156	156	158	200	216	24	25	25
InWt	67	82	92	724	725	864	2,377	2,849	2,968	199	205	205
TeFo	-	-	-	9	9	9	-	-	-	7	8	8
TrFo	83	96	121	-	-	-	1,160	1,413	1,516	-	-	-
Wood	25	30	34	251	255	251	320	396	421	160	166	165
ESV_{Cult} (av.)	26	30	37	102	104	104	624	764	817	40	41	41

Note: [1] See Table 3.4.

Considering the ESV_{Cult} (in €/ha/year) of each country on the Atlantic coastal zone (Figure 4.6 - Unit Cultural ecosystem service values (ESVCult) per country for 2005, 2010 and 2015 (in €/ha/year, 2015 price levels).Figure 4.6), countries with the smallest unit values (ESV_{Cult} < 10 €/ha/year) are concentrated on the African coastal zone, Greenland and Malvinas/Falkland Islands, due to the, earlier mentioned, low population density and large concentration of low value-added biomes. Countries with the highest value (ESV_{Cult} > 500 €/ha/year), are in Latin America & Caribbean, highlighting those such as Venezuela (1.3-1.6 thousand €/ha/year) and Brazil (1.0-1.3 thousand €/ha/year), followed by Costa Rica and Panama in Central America.

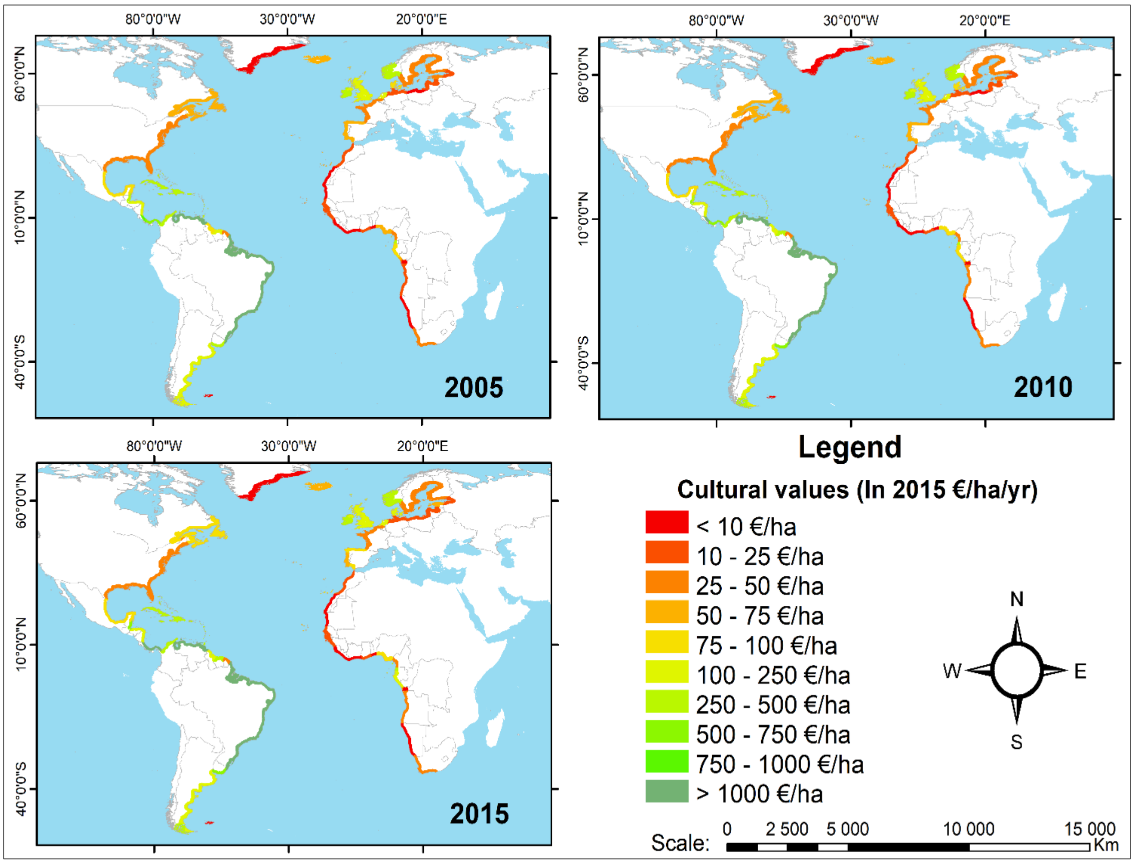

Figure 4.6 - Unit Cultural ecosystem service values (ESVCult) per country for 2005, 2010 and 2015 (in €/ha/year, 2015 price levels).

4.3.3. Total ecosystem service value changes on Atlantic coastal zone

After estimating the unit ecosystem service (ESV) values by type of service for each country and biome on the Atlantic coastal zone, these values are multiplied by the area per biome and aggregated to obtain the Total ecosystem service value (ESV_{Total}; in €/year). Our results indicate an increase in the ESV_{Total} over the years (see Table 9 and 10) – from 585.4 billion in 2005 to 709.7 billion Euros in 2015 (+21%).

Table 4.11 - Total ecosystem service value (ESVTotal) per continent and biome for 2005, 2010 and 2015 (in 109 €/year, 2015 price levels).

Continent \ ES[1]	**Africa**			**Europe**			**Latin America & Caribbean**			**North America**			**Atlantic coastal zone (Total study Area)**		
	2005	**2010**	**2015**	**2005**	**2010**	**2015**	**2005**	**2010**	**2015**	**2005**	**2010**	**2015**	**2005**	**2010**	**2015**
ESV_{Prov}	3.4	4.1	4.9	74.9	79.4	84.4	62.8	75.6	84.0	22.3	23.0	25.0	163.4	182.1	198.3
$ESV_{Reg\&main}$	1.5	1.8	2.1	81.5	83.2	86.3	13.3	15.2	16.2	48.1	49.8	52.9	144.3	150.0	157.5
ESV_{Cult}	4.9	5.8	7.1	40.1	40.7	44.7	219.0	268.3	286.7	13.6	14.0	15.4	277.7	328.8	353.9
ESV_{Total}	**9.9**	**11.6**	**14.1**	**196.5**	**203.3**	**215.4**	**295.1**	**359.1**	**386.9**	**83.9**	**86.9**	**93.3**	**585.4**	**660.9**	**709.7**

Note: [1] ESV_{Prov} = Provisioning ecosystem service values; $ESV_{Reg\&main}$ = Regulating & maintenance ecosystem service values; ESV_{Cult} = Cultural ecosystem service values.

Table 4.11 shows the ESV_{Total} for each type of ecosystem service, by continent. It is shown that ESV_{Cult} represents 50% of the ESV_{Total} on the Atlantic coastal zone (278-354 billion €/year), while ESV_{Prov} and $ESV_{Reg\&main}$ account, respectively, for around 27% and 22%. Most of the value of Cultural ES comes from the Latin America & Caribbean coastal zone (about 80%, 219-287 billion €/year). Europe represents around 55% of Regulating & maintenance services (82-86 billion €/year). The coastal zones of Europe and Latin America & Caribbean together generate nearly 85% of the Provisioning services (75-84 €/year billion and 63-84 billion €/year, respectively).

4.4. Discussion, reflection and relevance

4.4.1. Comparison with other coastal ecosystem service valuation studies

As to validate the ES values found in our analysis, we compare our results with similar previous studies in coastal areas. Studies performed until now offer rather disparate results (see Table 4.12). Average unit ecosystem service values in these studies, across all types of ES and all types of biomes, vary between 87 and 8,379 €/ha/year. Lowest unit ecosystem service values are observed in Martinez et al. (2007), which is explained by their coastal zone delimitation (100 km buffer from coastline, including a larger share of ES with lower unit value) and for world scale analysis (thus including a larger share of low unit value Desert/Snow areas). Alves et al. (2009), Roebeling et al. (2013) and

Paprotny et al. (2021) use a coastal zone delimited by a 10 km buffer (thus including a larger share of near-coast ES with higher unit value, such as Coastal Systems and Coastal Wetlands) and adopted value transfer; Paprotny et al. (2021) thereby also include values for Urban Systems (with high unit value).

In this study we present comparatively low average unit ecosystem service values (~460 €/ha/year), as it uses a coastal zone delimited by a 100 km buffer (thus including a larger share of ES with lower unit value). Our research covers the Atlantic coastal zone (thus also including the dry tropics areas) and it does not include values for Urban Systems. Also, our study uses value function transfer rather than simple value transfer – where the latter is, generally, known to lead to questionable ecosystem service valuation (Bateman, 2006; Reynaud & Lanzanova, 2017).

Table 4.12 - Average unit (in €/ha/year) ecosystem service values (ESV) for studies analyzing coastal ecosystem services (2015 price levels).

Authors	**Year of valuation**	**Scale/Location**	**Service analyzed**[1]	**ESV (€/ha/year)**
Martinez et al., (2007)	1997	World coast	ESV_{Total} Values from (Costanza et al., 1997)	86.9
Alves et al., (2009)	2006	Central Portuguese coast	ESV_{Total} Values from (Costanza et al., 1997)	1,237.9
Roebeling et al., (2013)	2000	European coast	ESV_{Total} Values from (Costanza et al., 1997)	969.6
Paprotny et al., (2021)	2018	European coast	ESV_{Total} Values from (de Groot et al. 2012; Costanza et al., 2014)	8,378.5
This study	2005	Atlantic coast	ESV_{Total} Values based on (Magalhães Filho et al., 2021)	459.7

Note: ESV_{Total} = Total ecosystem service values.

4.4.2. Reflecting on ecosystem service values over time

As demonstrated in this study, natural areas endowed with greater ES values are decreasing, while the total and unit ES values of the Atlantic coastal zone are increasing over the years. To understand this change, it is important to acknowledge that ecosystems do not provide any service to people without the co-production of human-nature interactions (human capital), their communities (social capital) and their built environment (built capital; Outeiro et al., 2017). This co-production process is presented in Figure 4.7a, which shows that ES do not flow directly from natural capital to human wellbeing. Rather, it is only through the interaction with the other three forms of capital that natural capital can provide benefits to people (Costanza et al., 2014; Palomo et al., 2016). This is why sparsely populated areas presented lower ES values, as for example the African coastal zone, while more densely populated and higher income areas presented higher ES values, such as the European coastal zone.

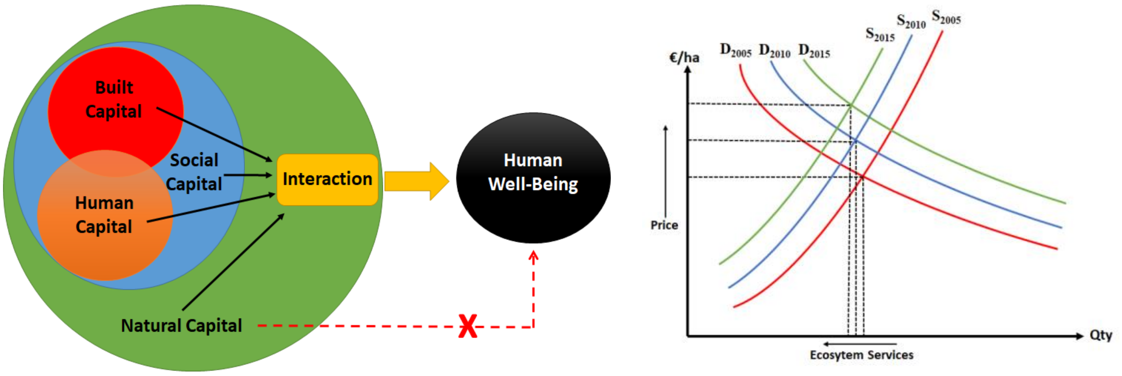

Figure 4.7 - A) Interaction between the different capitals that provide human well-being; B) Supply and demand curves of ESV over time (adapted from, Costanza et al., 2014).

Another important point to consider is the ecosystem service demand versus supply dilemma (Figure 4.7b). First, note that the stocks and flows of ecosystem services by nature tend to be inelastic (the ES supply side) while the consumption of ES by humans tends to be elastic (the ES demand side; Costanza et al., 2014). Second, ES demand tends to increase with higher population (*PDen*) – indicating that proximity to the market of potential visitors results in higher ecosystem service values (Van Houtven et al., 2007; Ghermandi & Nunes, 2013; Ghermandi et al., 2013) – leading to an outward shift of the demand curve and increase in equilibrium value (price). Hence, ecosystem service values are increasing with population growth over time, while noting that the marginal increase in ESV is decreasing in population density (Van Houtven et al., 2007; Hynes et al., 2013). Third, if not adequately managed, however, excess demand will lead to degradation of ecosystems and a reduction in the supply of ecosystem services – leading to an inward shift of the supply curve and, also, an increase in equilibrium value (due to scarcity; see Figure 4.7b). Hence, ecosystem service values are increasing with ecosystem (service) scarcity over time (de Groot, et al., 2012). Forcing the full internalization of all environmental costs into the cost structure of products and services throughout production and value chains, will lead consumer market prices to reflect these costs and, subsequently, to a reduction in demanded quantity and, thus, a reduction in degradation and transformation of natural systems.

Thus, ESV growth deserves caution because through an over-simplistic analysis a basic interpretation could be derived in that the “richness” of ES available in a country is growing. However, in case a country presents income stagnation, the value of the ES will also decrease. Analogously, a decrease in population may also lead to a decrease in ESV, as human and social capital will be lower over time. Some European countries, such as Portugal, exhibit these characteristics. Therefore, policies are needed for conservation and recovery of biomes that provide ES that are critical for human well-being (Costanza et al. 2014). It is recognized that biosphere capacity serves as the basis for human well-being, and that human well-being is embedded in and rests on a resilient biosphere (Folke et al., 2016).

4.4.3. Relevance for coastal management and policy makers

The supply of ES is critical to human wellbeing, though can be impaired by changes in complex dynamic ecosystems induced by land use transformation, overexploitation and pollution (Reyers, et al., 2013). Thus, to change the status-quo and explore alternative transformative pathways, societies need to manage common natural capital in a more effective and sustainable way (Zhang & Gangopadhyay, 2015; Vilassante et al., 2022). Environmental economics, through ecosystem service valuation, mapping and assessment, helps decision makers to adequately balance the benefits of preserving or protecting healthy natural ecosystems against the benefits of developing a region and the costs of recovering ecosystems from exploitation and/or pollution (Phillips & Zeckhauser, 1998).

All ecosystems deliver a broad range of services, some of which have particular economic or social value. However, many ES are either undervalued or have no direct value in current decision-making processes, although crucial to human well-being. For the most part, policy decision-making processes take account only of traded goods. They thereby ignore the value of the majority of ES that will be altered by transformation, exploitation and pollution. The valuation of benefits enables decision-makers to place a value on changes in services that are not captured by markets (Dasgupta, 2021). For example, there is currently an increased effort to analyze the link between physical and mental human health and wellbeing and the marine environment (Bratman, 2019). This is highly relevant because the ES concept is not fully incorporated in EU policies yet, although it is gradually becoming more integrated, particularly in policies governing natural ecosystems (Brouwma et al., 2018). Balvanera et al., (2022) argue that global frameworks are needed to guide consistent monitoring of changes in human-nature interactions across space and time, as to understand how ecosystems support societies and can inform policy design. They consider that Monitoring Essential Ecosystem Service Variables (EESVs) can provide a comprehensive picture of how links between nature and people are changing – similar to the United Nations System of Environmental and Economic Accounting - Experimental Ecosystem Accounting (SEEA-EEA) that provides a coherent accounting approach to the measurement of environmental assets and ecosystem services (UN, 2014).

Commonly, economic theory and research fails to incorporate environmental values and disregard their economic impact on human welfare (Roebeling et al., 2013; Mach et al., 2015). However, to halt the loss and degradation of coastal natural capital, the reinforcement of ecosystem conservation policies and the improvement of the way resources are used, are crucial to attain sustainable development. Integrated Coastal Zone Management (ICZM, Directive 2002/413/EC) and the Marine Strategy Framework Directive (MSFD; Directive 2008/56/EC), which provide an integrated approach to the protection of coasts and marine waters in Europe, rely on environmental and ecosystem accounting, mapping and valuation to assess environmental, social and economic impacts of planning decisions. Estimates of coastal ES values, expressed in monetary units, like those in this research, are thereby essential to raise awareness in societies about the significance of these services provided by natural capital relative to other services provided by human, social and built capital (Costanza et al., 2014). Based on simple value transfer, previous studies have done this at global level (e.g. Costanza et al., 1997; de Groot et al., 2012; Costanza et al., 2014), as well as for world coastal (e.g. Martinez et al., 2007; Ghermandi & Nunes, 2013; Rao et al., 2015), continental coastal (e.g. Roebeling et al., 2013) and national coastal (e.g. Alves et al., 2009) ecosystems. ES value estimates in these studies are, however, not context specific – i.e. they do not consider local characteristics, such as ecosystem location/accessibility, quality, territorial extension and socio-cultural dimensions, which are essential when estimating ecosystem service values (e.g. Outeiro et al. 2015; Lopes & Villasante, 2018).

Insight into the distribution of coastal ES and values across types of biomes, services, countries and continents, as provided in this study, is key to identify what values are at stake and for whom, in particular in the context of the increasing need for equitable distribution of benefits. Land-sea interactions (see MSFD; Directive 2008/56/EC) and global changes, such as population growth, economic development and climate change, put pressure over these coastal ES and values and, hence, it can be assessed what biomes, services, countries and continents are mostly affected. Again, based on simple value transfer, such ecosystem service value loss assessments have been performed for European coastal (e.g. Roebeling et al., 2013, Paprotny et al., 2021) and national coastal local coastal (e.g. Alves et al., 2009; Hynes et al., 2013; Mentzafou et al., 2020) ecosystems, with the aim to support coastal protection planning.

Finally, insight in the importance of human, social and built as well as natural capital services and values is crucial in the definition of coastal adaptation strategies. Global changes put pressure over coastal human, social and built capital services and values as well as over natural capital services and values. Coastal adaptation strategies, including retreat, accommodation, and protection measures (EEA, 2006, EEA, 2013), should be based on full welfare analyses that consider human, social and built as well as natural capital services and values (Bosello et al., 2007). This will, for example, lead to coastal adaptation strategies that not only protect the traditional human, social and built capital services and values, but also, natural capital services and values (Roebeling et al., 2018).

4.5. Conclusions

This study presents a global ecosystem service value function application to map and assess the ecosystem service values (ESV) associated with Provisioning (ESV_{Prov}), Regulating & maintenance ($ESV_{Reg\&Main}$) and Cultural (ESV_{Cult}) ecosystem services (ES) for the Atlantic coastal zone. Results show that, although there was a decrease in natural areas along the Atlantic coastal zone over the period 2005-2015, the ESV increased over time, mainly due to the increase in population density (*PDen*) and national income (*GNI*).

The economic value of ES along the Atlantic coastal zone increased by 21%, from 585 billion to 710 billion €/year between 2005-2015. Tropical forests have been the highest appreciated biome, valuing 177-234 billion €/year over this period. Across the considered continents, the largest total ecosystem service value (ESV_{Total}) was found for Latin America & Caribbean, mainly due to the high value associated with Cultural services. Lowest ESV_{Total} were found for Africa, due to its lower population density and income and, also, the relatively large presence of low-value biomes such as Deserts.

Some caveats remain. First, we used global ecosystem service value functions from Magalhães Filho et al., (2021), which is based on data from the Ecosystem Service Valuation Database that includes more than 320 studies published until 2009. Since then, numerous primary valuation studies have been developed – as evidenced by the recently updated ESVD (October, 2021) that now includes over 900 studies published until 2020 (https://www.esvd.net/). Second, for this assessment we considered a null value (0 €/ha/year) for urban areas, as the global value functions did not present any ecosystem service value for urban biomes, although it is known – and we acknowledge so – that there are values associated with urban ecosystems as they contain green areas (e.g. parks, squares, vegetable gardens, woods) and other services that urban areas themselves may provide. Finally, it is important to highlight that the observed increase in ESV over the years deserves careful consideration. A possible economic slowdown and/or population decrease in combination with the current natural capital consuming economic model for growth, could lead to jeopardizing the ecosystems, services and values due to increasing demand for and decreasing supply of ES.

This study expects to serve as a warning signal by presenting which ES and biomes have the highest associated values in each region along the Atlantic coastal zone as well as which countries have the highest ES value associated with their coastal zone. Moreover, it emphasizes the need to maintain and conserve natural ecosystems for present and future generations.

CHAPTER 5

5. ECOSYSTEM SERVICES VALUES AT RISK IN THE ATLANTIC COASTAL ZONE DUE TO SEA-LEVEL RISE AND SOCIOECONOMIC DEVELOPMENT[*]

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ABSTRACT

Uncertainties about the future extent of sea-level rise (SLR) and socioeconomic development will determine the future of coastal ecosystem services and values. This study analyzes the joint impact of flooding and socioeconomic development on the future ecosystem services and values in the Atlantic coastal zone by 2100. To this end, flood probability maps (using the Uncertainty Bathtub Model; uBTM) and local ecosystem service value (ESV) estimates (using meta-analytic based global ecosystem service value functions for Provisioning, Regulating & maintenance, and Cultural ecosystem services across 12 biomes) are derived for a wide combination of Representative Concentration Pathway (RCP) and Shared Socioeconomic Pathways (SSP) scenarios to obtain future values of coastal ecosystem services (ES). Results show that the higher potential of ESV at risk is associated with RCP 8.5 and SSP5, i.e. the scenario associated with a narrative related to fossil-fueled development. For this scenario, by 2100, the coastal zone with the highest probable losses in Provisioning ESV is Europe (~5.9 € billion/year), for Regulating & maintenance ESV this is North America (~6.0 € billion/year) and for Cultural ESV this is South America (~21.3 € billion/year). Countries facing highest relative risk of losing Provisioning ESV are the Netherlands (10.6%), United States (7.4%), and Mauritania (5.8%). For Regulating & maintenance ESV, the top 3 countries impacted are Mauritania (17.6%), the Netherlands (10.0%) and Argentina (8.0%). For Cultural ESV, the countries are Mexico (19.0%), Denmark (18.1%) and Sweden (15.6%). Changes in ESV are exponentially related to flood risk and economic growth, such that small changes in flood or income lead to large changes in ESV. Unlike previous studies, the ESV functions used are dependent on time and local factors, such as population and income. Although population and income growth results in an increase in ESV, it also emphasizes the ecosystem service values at risk. Thus, sea-level rise and socioeconomic changes impact ecosystem services and values – directly affecting the well-being of the world population. The unequal distribution of coastal ecosystem service value losses across continents and countries highlighted in this work is important to identify what values are at risk and for whom. Adaptation measures and strategies can, in turn, be defined.

5.1. Introduction

Coastal areas are among the most important regions for humanity. Indeed, more than 30% of the world's population live in coastal communities – which are twice as densely populated as inland areas (MEA, 2005; Barbier et al., 2008; Rao et al., 2015; Neumann et al., 2015; McMichael et al., 2020) – and 80% to 100% of the total population of more than half of coastal countries live within 100km from the coastline (Burke et al., 2001; Neumann et al., 2015; McMichael et al., 2020).

Coastal ecosystems are diverse, highly productive, ecologically important at the global scale, and highly valuable for the wide range of services they supply to human beings (de Groot et al., 2012; IPCC, 2013). These include provisioning services, such as the supply of food via fishery production, fuelwood, energy resources and natural products; regulating & maintenance services, such as shoreline stabilization, nutrient regulation, carbon sequestration, detoxification of polluted waters and waste disposal; and cultural services, such as tourism, recreation, aesthetics, spiritual experience, and religious and traditional knowledge (TEEB, 2010; Gundersen, et al., 2016). These ecosystem services (ES) and their associated values are of inestimable importance to life and human wellbeing, both to communities living in coastal zones and to national economies and global trade. However, they are vulnerable to sea-level rise (Nicholls & Tol, 2006; Roebeling et al., 2013; Rezaie et al., 2020).

An important way to investigate vulnerability and human dependence on coastal ES is to examine their estimated values, paying attention to their variation (de-/increase) over time. Estimating their value provides insight in the elements (such as site and context characteristics) determining their high and low values and, at the same time, inform policymakers (Rao et al., 2015; Su & Peng, 2021). In addition, assessing future scenarios, involving climate change and socioeconomic development, provides insight into possible losses in ES values over time and measures to mitigate them (de Lima et al., 2021; Roebeling et al., 2013).

Scenarios provide an essential tool for climate change research and assessment. They help us to recognize long-term consequences of near-term decisions and provide researchers with information to explore different potential futures in the context of fundamental future uncertainties (Riahi et al., 2017). Important examples of such scenarios include previous scenarios by the Intergovernmental Panel on Climate Change (1990 IPCC Scenario A

[SA90], 1992 IPCC Emissions Scenarios [IS92] and Special Report on Emissions Scenarios [SRES]) and the more recent Representative Concentration Pathways (RCP) and Shared Socioeconomic Pathways (SSP) (Moss et al., 2010; van Vuuren et al., 2011; Riahi et al., 2017). Together, RCP and SSP can provide a powerful framework to determine possible environmental and socioeconomic impacts from climate and socioeconomic change until the year 2100.

Contemplating the complexity of SLR hazards, flood modelling using Geographic Information Systems (GIS) is crucial to improve coastal management A widely used, simple and transparent approach to provide a first-order approximation of SLR-induced flooding is the so-called Bathtub method, which assumes that coastal land areas with elevation equal to, or below, the projected height of global sea-level will be flooded (NOAA, 2012). The Uncertainty Bathtub Model (uBTM), a modified version of this technique that combines the uncertainty of sea-level projections and the vertical error of a digital elevation model (DEM), defines the probability of the sea-level to flood a considered zone, using the level of uncertainty associated with the DEM and the sea-level rise projections (e.g., de Lima et al. 2021; de Lima & Bernardes, 2020; Eastman, 2021).

Various papers seeking to value coastal ecosystem services and values have been published over the last decades. Martinez et al. (2007) studied the economic value provided by ecosystems services for the world coast (for the year 2003), using unit value transfer based on values from Costanza et al. (1997). Roebeling et al. (2013) studied past (1975) to future (2050) land cover and ES value losses from coastal erosion along the European coast, using climate change scenario (SRES B1 and A1Fi) simulations from the Dynamic and Interactive Vulnerability Assessment (DIVA) tool to explore future coastal erosion projections (Hinkel & Klein, 2009) in combination with unit value transfer based, also, on values from Costanza et al. (1997). More recently, Paprotny et al. (2021) studied the ES value losses that could occur due to SLR-induced coastal erosion for the years 2050 and 2100, adopting coastal erosion projections from Vousdoukas et al. (2020) under two future emission scenarios (RCP 4.5 and RCP 8.5), while also using unit value transfer based on updated values from de Groot et al. (2012) and Costanza et al. (2014). Although studies have accounted for the temporal evolution of the coast, coastal erosion and ecosystem service value losses based on updated unit ecosystem service values, they assumed socioeconomic conditions to remain unchanged (over time) and continue to be based on unit value transfer (i.e., values from the primary study site are directly applied to the secondary policy site; see e.g., Brander, 2013).

Hence, the objective of this study is to analyze the joint impact of flooding due to sea-level rise and socioeconomic development on future ecosystem services and values in the Atlantic coastal zone by 2100. To this end, we use the Uncertainty Bathtub Model (uBTM; to assess areas at risk of flooding) and combined climate (RCP 4.5 and 8.5) and socioeconomic (SSP1-SSP5) scenarios (for 2015 and 2100) in combination with meta-analytic based global value function transfer (for estimating local Provisioning, Regulating & maintenance and Cultural ecosystem service values). The study covers 5 continents and about 60 countries on the Atlantic coastal zone.

5.2. Methods and data

The methodology integrates multiple datasets and models to obtain projections of ecosystem service values at risk of flooding (see Figure 5.1). This section describes the used Ecosystem service value functions (Section 5.2.1), the applied Uncertainty Bathtub Model (uBTM; Section 5.2.2) and the used Climate change and socioeconomic scenarios (RCP and SSP; Section 2.3) as to determine the ecosystem service values at risk in 2015 and 2100 (Section 5.2.4).

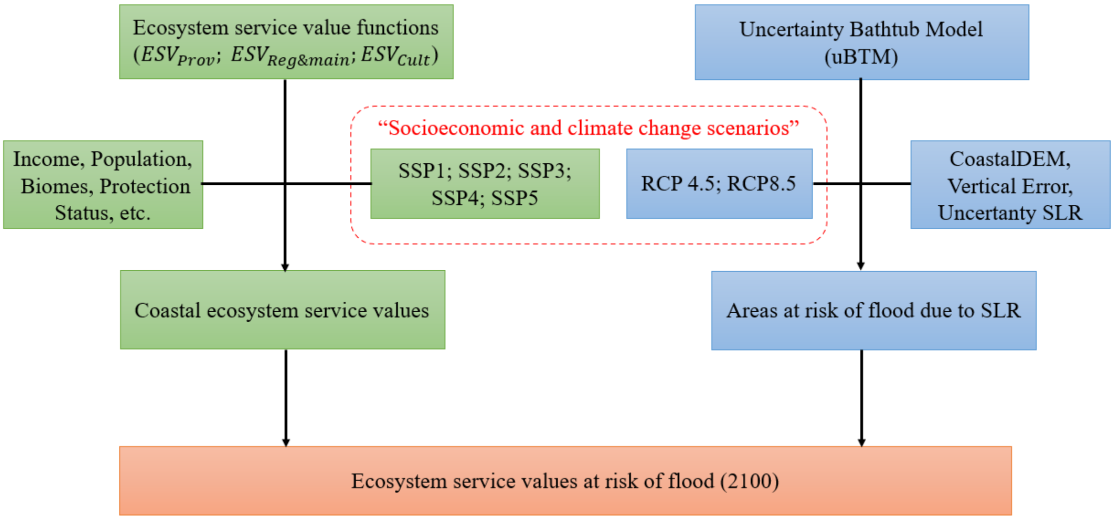

Figure 5.1- Flowchart of the main elements of the methodology.

5.2.1. Ecosystem service value functions

Meta-analytic based global ecosystem service value functions from Magalhães Filho et al. (2021) were used for Provisioning, Regulating & maintenance and Cultural ecosystem services. The respective ecosystem service values are a function of income, population density, percentage of terrestrial area totally or partially protected, percentage of marine protected area, percentage of agricultural land and percentage of forest land, with dummies for biome and continent (see Table 5.1).

Table 5.1 - Meta-Analysis (MA) variable description and sources (source: Magalhães Filho et al. 2021).

Variables	**Description**	**Data source**
APer	Agricultural land that refers to the share of land area that is arable, under permanent crops, and under permanent pastures, by percentage of land area.	FAOSTAT (2021)
FPer	Forest area with natural or planted stands of trees of at least 5 meters in situ, by percentage of land area.	
MProt	Percentage of marine protected areas, from territorial waters of a country.	World Bank (2021)
TProt	Percentage of terrestrial areas totally or partially protected, designated by national authorities.	
GNI	Gross National Income per capita, using purchasing power parity rates.	
PDen	Population density is midyear population divided by land area in square kilometres.	
Dummies	**Description**	**Data source**
CSys; CWet; CoRf; CuAr; Dser; FrWa; Gras; InWt; Mari; TeFo; TrFo; Wood	**Biomes:** Coastal System; Coastal Wetland; Coral Reef; Cultivated Area; Desert/Snow; Fresh Water; Grassland; Inland Wetland; Marine; Temp./Bor. Forest; Tropical Forest; Woodland.	ESVD (20200)
Euro; Asia; Ocea; LaAm; NoAm; Afri	**Continents:** Europe; Asia; Oceania; Latin America & Caribbean; North America; Africa.	
FProt; PProt; NProt	**Protection Status:** Fully Protected; Partially Protected; Not Protected.	

The value functions take a semi-log specification, which implies that the marginal effect of a change in ESV depends on income and population density (Magalhães Filho et al., 2021). Coefficient values for the Provisioning, Regulating & maintenance and Cultural ecosystem service value functions are given in Table 5.2.

Table 5.2 - Value function model specification for ecosystem services[1] (source: Magalhães Filho et al. 2021).

Explanatory variables[2]	**ESV**$_{\textbf{Prov}}$[1]	**ESV**$_{\textbf{Reg\&main}}$[1]	**ESV**$_{\textbf{Cult}}$[1]
	Coef	*Coef*	*Coef*
CONSTANT	-6.41	-3.46	-7.37
CSys	2.68	3.98	-
CWet	2.22	4.19	1.35
CoRf	-	4.68	2.48
CuAr	3.69	3.07	
FrWa	2.17	-	-
IWet	2.03	4.77	1.48
Mari	2.18	-	-2.47
TeFo	-	3.35	-3.09
TrFo	2.06	2.4	1.2
FProt	-	-1.73	-
PProt	-	-	1.17
Asia	-	-	-1.75
Ocea	-	-	-1.33
LaAm	1.76	-	1.33
Afri	-	-2.12	-
Aper	-0.04	-	-
FPer	-	-0.02	-
Mprot	-	-0.02	-0.05
TProt	-0.05	-0.05	-
ln_GNI	0.87	0.49	1.04
ln_PDen	0.59	0.66	0.48

Notes: Dependent variable is ln_ESV$_i$.

[1] ESV$_{\text{Prov}}$ = Provisioning ecosystem service values; ESV$_{\text{Reg\&main}}$ = Regulating & maintenance ecosystem service values; ESV$_{\text{Cult}}$ = Cultural ecosystem service values.

[2] See Table 1 for variable descriptions. *Gras*, *NProt* and *Euro*, are the dummy variables used as the basis for the analysis.

5.2.2. Uncertainty Bathtub Model (uBTM)

GIS techniques are widely used for understanding coastal inundation processes and assessing coastal zone hazards in scientific research, coastal management and spatial planning (e.g., Desai et al. 1991; Rajawat et al. 2005). One of the most used GIS-based approaches is the Bathtub Method (see e.g. Klein & Nicholls 1998, Williams & Lück-Vogel, 2020).

The exponential increase of Google Earth Engine (GEE; Gorelick et al., 2017), in terms of available data and capability to address very-large datasets with a high spatial resolution, has become a powerful cloud-based platform capable of harnessing large-scale problems on coastal management in a new manner (de Lima et al., 2021). Through GEE the uBTM was implemented, a technique that combines the Uncertainty of SLR Projections (USP) and the Vertical Error (VE) of a Digital Elevation Model (DEM; see Figure 2a). The uBTM is based on the Terrset Sea-level Impact tool (Eastman, 2021), and tests the uncertainty of sea-level rise projections with vertical errors in the DEM, creating a rate from 0 to 100% (which indicates the probability of a specific area to be flooded by sea-level rise).

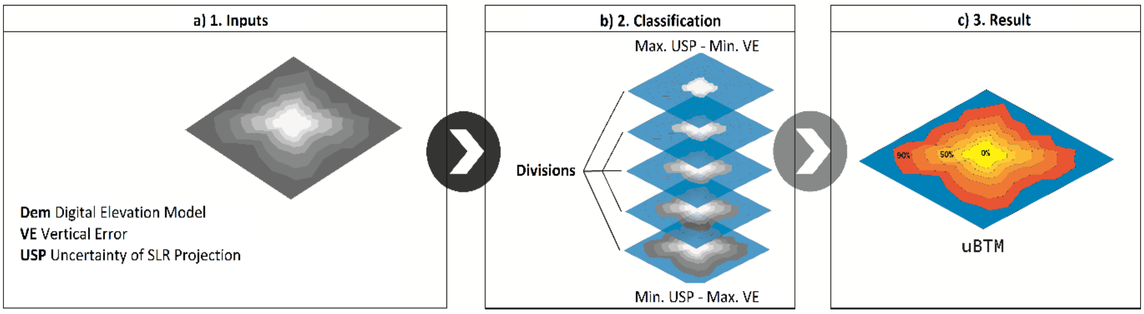

Figure 5.2 - The Uncertainty Bathtub Model conception (adapted from de Lima et al., 2021).

In this study, we adopted the uBTM methodology by de Lima et al. (2021; see Figure 5.2). The model adopts the lowest vertical error of a DEM and the sea-level rise projection with the highest estimation (Figure 5.2b). The areas have a 0% probability of being submerged when the maximum error of DEM elevation is compared with the maximum sea-level rise projection and the area appears not submerged, even with pessimistic settings, and on the other hand, the areas have a 100% probability of being submerged when the maximum error of DEM elevation is compared with the lowest sea-level rise projection and the area appears submerged, even with optimistic settings. The definition of these extreme situations allows establishing a probabilistic scale of percentages (between 0 to 100%; see Figure 5.2c). As inputs, we use of the CoastalDEM, a global coastal DEM provided in Kulp & Strauss (2018; see https://go.climatecentral.org/coastaldem/), adopting as VE the value of 2.50 m, which means a possibility of error variation of 1.25 m.

5.2.3. Climate change and socioeconomic scenarios

Climate change is driven by a myriad of societal factors over decades and centuries to come. This raises questions such as "What will happen?" and try to predict their impacts. But the future, while uncertain, is not entirely unknowable. Scenarios can be used to explore "What can happen?" and even "What should happen?" given the fact that we are able to shape our future (Auer, 2020). In this way emerge the climate change scenarios, which are not future predictions but, rather, projections of what can happen by creating plausible and consistent descriptions of possible climate change futures. They can also constitute coherent descriptions of pathways towards certain goals (Carlsen *et al.*, 2017; Auer, 2020).

Perhaps one of the most discussed scenarios are the Representative Concentration Pathways (RCP), a climate forcing group of scenarios from the fifth IPCC report (IPCC, 2013). The RCP are a set of four new pathways developed for the climate modeling community as a basis for long-term and near-term modeling experiments. The four RCP together span the range of year 2100 radiative forcing values found in the open literature, i.e. from 2.6 to 8.5 W/m^2. The RCP are the product of an innovative collaboration between integrated assessment modelers, climate modelers, terrestrial ecosystem modelers and emission inventory experts (van Vuuren et al., 2011). The RCP scenarios provide datasets as different global warming increase estimates and SLR projections. This set of scenarios is divided into (IPCC, 2013):

i. RCP 2.6, with a peak in radiative forcing at 3 W/m^2 (90 ppm CO_2 eq.) before 2100 and then a decline to 2.6 W/m^2 by 2100. SLR Mean (range) between 2081-2100: 0.40 m (0.26 to 0.55);

ii. RCP 4.5, without overshoot pathway to 4.5 W/m^2 in radiative forcing (~ 650 ppm CO_2 eq.) and stabilization after 2100. SLR Mean (range) between 2081-2100: 0.47 m (0.32 to 0.63);

iii. RCP 6, without overshoot pathway to 6 W/m^2 in radiative forcing (~850 ppm CO_2 eq) and stabilization after 2100. SLR Mean (range) between 2081-2100: 0.48 m (0.33 to 0.63);

iv. RCP 8.5, with an increasing radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2 eq) by 2100. SLR Mean (range) between 2081-2100: 0.63 (0.45 to 0.82).

RCP 2.6 is known as the best-case scenario, the RCP 4.5 and RCP 6 are intermediate scenarios, and RCP 8.5 is the worst-case scenario.

Other scenarios, created later by the 6th Climate Model Intercomparison Project (CMIP6; O'Neill, 2017), are the Shared Socioeconomic Pathways (SSP), a group socioeconomic scenarios. They were built as different socioeconomic reference developments spanning the space of socioeconomic challenges to mitigation and adaptation (O'Neill et al., 2014; van Vuuren et al., 2014). The SSP comprise five narratives describing alternative socioeconomic developments, including sustainable development, regional rivalry, inequality, fossil-fueled development and middle-of-the-road development, giving rise to scenarios estimating quantified population, income and urbanization trajectories as well as qualitative assumptions on energy and land use sectors (Riahi et al., 2017). A multi-model approach was used for the elaboration of the energy, land-use emissions trajectories of SSP-based scenarios (Eyring et al., 2016). The SSP provide five pathways about future socioeconomic developments as they may unfold in the absence of additional policies and measures to limit climate forcing or enhance adaptive capacity. The SSP narratives are (Riahi et al., 2017):

i. SSP1, "Sustainability – Taking the Green Road": this future poses low challenges to mitigation and adaptation, global population peaks mid-century, emphasis on human well-being, environmentally friendly technologies and renewable energy, and strong and flexible institutions at global, regional, and national level;

ii. SSP2, "Middle of the road": this future poses medium challenges to mitigation and moderate challenges to adaptation, population growth stabilizes toward the end of the century, current social, economic and technological trends continue, and global and national institutions make slow progress toward achieving sustainable development goals;

iii. SSP3, "Regional rivalry – A rocky road": this future poses high challenges to mitigation and adaptation, population growth continues with high growth in developing countries, emphasis on national issues due to regional conflicts and nationalism, economic development is slow and fossil fuel dependent, weak global institutions and little international trade;

iv. SSP4, “Inequality – A road divided”: this future poses low challenges to mitigation and high challenges to adaptation, population growth stabilizes toward the end of the century, growing divide between globally-connected, well-educated society and fragmented lower income societies, unrest and conflict becomes more common, and global, regional and national institutions are ineffective;

v. SSP5, “Fossil-fueled development - Taking the highway”: this future poses high challenges to mitigation and low challenges to adaptation, global population peaks mid-century, emphasis on economic growth and technological progress, global adoption of resource and energy intensive lifestyles, and lack of environmental awareness.

To understand what these SSP narratives mean for future greenhouse gas emissions and climate change, those assumptions were translated into quantitative projections for future energy and land use through Integrated Assessment Models (IAM) representing the world’s coupled energy-land-economy-climate system and its development over the 21st century. Based on socioeconomic scenarios, IAM derive consistent pathways for macroeconomic, energy system, and land use variables and project resulting emissions of greenhouse gases and air pollutants until the end of the century (Auer, 2020).

For the present study, the SLR scenarios RCP 4.5 and RCP 8.5 were used, which is justified due to the construction of the narrative where we aim to find the main losses of ecosystem services due to rising sea-levels. For this reason, we adopted an intermediate and worst-case scenarios. It is important to highlight the absence of glacial isostatic adjustment for SLR, which is more pronounced at high latitudes and, thus, not relevant in this analysis.

For socioeconomic data we use the range over the Shared Socioeconomic Pathways (SSP), which is the standard set of socioeconomic scenarios used in climate change-related research and consists of five alternative futures describing different challenges to adaptation and mitigation (Kriegler et al, 2012; O'Neill et al., 2017). As to estimate the future ESV for 2100, we use the SSP Public Database (Rhiahi, 2017) to obtain the values for the explanatory variables for the SSP scenarios (see Table 5.3). Note that the SSP scenarios do not provide information on the percentage of marine (*MProt*) and terrestrial (*TProt*) protected areas and, hence, values adopted were the same as those for the reference year (RY; 2015).

Table 5.3 - Summary of the explanatory variables used in the value functions by continent.

Variables[1]	**Scenario/Continent**[2]	**Africa**	**Central America**	**Europe**	**North America**	**South America**
APer (%)	*RY (2015)*	43.33	32.84	41.33	35.39	29.60
	SSP1 (2100)	56.19	47.68	33.20	40.30	39.64
	SSP2 (2100)	56.20	49.02	46.20	46.41	40.65
	SSP3 (2100)	76.57	51.83	47.45	42.65	43.35
	SSP4 (2100)	71.46	30.22	48.63	36.94	27.23
	SSP5 (2100)	59.18	46.45	39.70	39.01	38.15
FPer (%)	*RY (2015)*	36.23	44.02	33.15	35.35	54.46
	SSP1 (2100)	28.78	42.32	38.28	38.63	52.37
	SSP2 (2100)	35.37	35.53	34.58	34.20	43.96
	SSP3 (2100)	13.98	40.07	30.86	32.67	49.58
	SSP4 (2100)	8.95	44.93	33.49	35.82	55.35
	SSP5 (2100)	25.93	41.74	33.03	34.67	51.64
Mprot (%)	*RY (2015)*	1.73	3.10	17.37	14.74	5.81
Tprot (%)	*RY (2015)*	18.26	28.18	21.60	12.31	19.70
GNI (€/2015)	*RY (2015)*	4 320.04	7 826.24	27 271.03	29 728.37	10 291.13
	SSP1 (2100)	69 597.16	74 730.87	87 346.15	92 689.13	77 375.15
	SSP2 (2100)	49 358.49	58 346.58	86 774.94	80 821.28	63 005.93
	SSP3 (2100)	15 973.51	23 319.10	60 763.05	63 774.96	29 126.23
	SSP4 (2100)	20 502.24	33 036.82	95 692.93	95 619.62	59 225.40
	SSP5 (2100)	115 993.89	122 992.29	136 830.12	150 547.99	128 801.76
PDen (Hab/Km^2)	*RY (2015)*	71.96	92.86	137.07	33.65	19.27
	SSP1 (2100)	71.42	66.52	104.24	58.76	127.32
	SSP2 (2100)	130.84	123.38	153.25	43.74	23.08
	SSP3 (2100)	172.99	175.87	109.73	47.91	29.48
	SSP4 (2100)	160.03	138.60	130.50	36.95	19.84
	SSP5 (2100)	99.44	89.06	204.32	43.76	19.49

Notes: [1] See Table 1 for variable descriptions.

[2] RY = Reference Year; SSP= Shared Socioeconomic Pathways.

As highlighted, we used socioeconomic information from SSP linked to RCP sea level rise scenarios. Considering predispositions to mitigate and adapt to climate change, we combined RCP 4.5 with SSP1, SSP2 and SSP4, and the RCP 8.5 with SSP2, SSP3 and SSP5 (following Auer, 2021; see Figure 5.3).

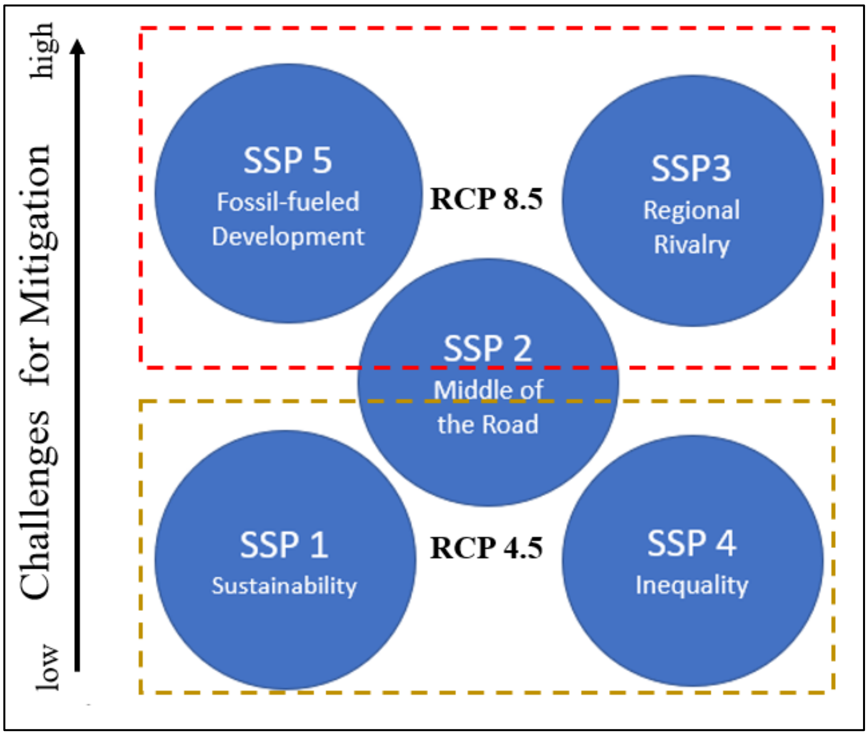

Figure 5.3 – Scenario combinations between RCP and SSP (adapted from Auer, 2021).

5.2.4. Data Sources

To proceed with the mapping of the Atlantic coastal zone, we based our calculations on a delimited area within 100 km of the coastline (following Burke et al., 2001; Martínez et al., 2007), covering 59 countries. Countries with a coastal area less than 10 ha were not considered in the analysis, and the islands located in Central America were united to form the Caribbean small states region. The study area was delimited according to Figure 5.*4*.4.

Next, we reclassify land cover data from the Climate Change Initiative - Land Cover (CCI-LC; ESA, 2021) for the year 2015 to match the biomes used in the meta-analytic based global ecosystem service value functions from Magalhães-Filho et al. (2021). Reclassified data is then extracted for the Atlantic coastal zone. The final reclassification of land cover to biome is as follows: Grassland, Coastal System, Coastal Wetland, Cultivated Area, Desert/Snow, Forest (Temperate/Boreal of Tropical), Water (Fresh Water or Marine), Inland Wetland, Urban Area (see Figure 5.4).

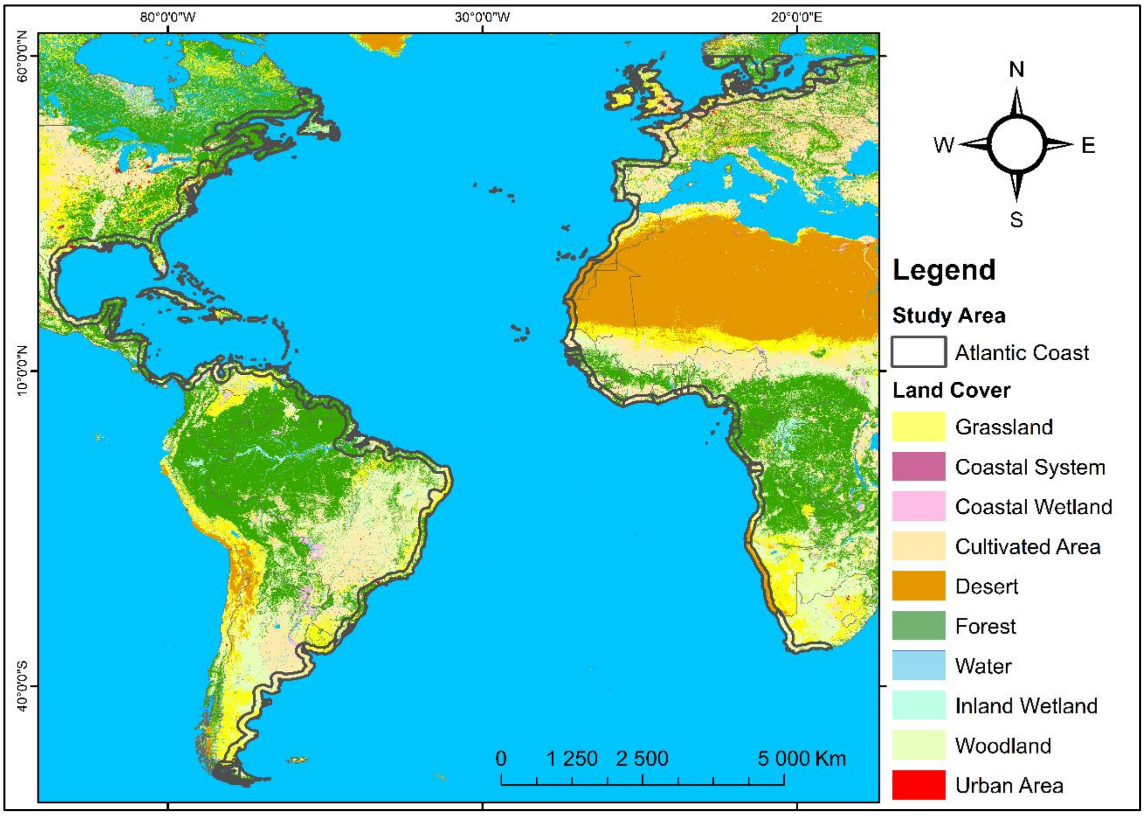

Figure 5.4 - Map of Land cover in Atlantic Coastal Zone in 2015.

The land cover database provides the area of each biome as well as the biomes at risk of flooding according to the uBTM. Value functions are used to calculate the Provisioning, Regulating & maintenance and Cultural ecosystem service values per biome, for each country for the years 2015 and 2100. The ES unit value (€/ha/year) per biome is determined, together with the corresponding evolution over the years. In turn, ESV are computed for each land use by multiplying the ES unit value per biome by the corresponding area, according to the period under analysis. For the RY (2015) we use data from FAOSTAT (2021) and World Bank (2021), and for 2100 we adopt data from SSP 1 to 5 from IIASA (2020). For the Uncertainty Bathtub Model application, we use the digital elevation model from CoastalDEM (see Section 5.2.2) and the SLR Projections from RCP 4.5 and 8.5 (IPCC, 2013; see Section 5.2.3).

5.3. Results

5.3.1. Unit ecosystem service values

Results are presented for the different ecosystem service values (ESV_{Prov}, $ESV_{Reg\&Main}$ and ESV_{Cult}; in €/ha/year) and their sum (ESV_{Total}) by applying the meta-analytic based ecosystem service value functions, adopting the reference year (RY) values of explanatory variables, for 2015. For a better understanding of the results, we show the unit ecosystem service values for each type of biome (in €/ha/year) in Table 5.4 Note that the highest ESV were for the Inland Wetlands (ESV_{Total} = 1319.5 €/ha/year), Coastal Wetlands (ESV_{Total} = 930.8 €/ha/year) and Coastal Systems (ESV_{Total} = 602.2 €/ha/year) biomes. These present a high value due to the wide range of services provided (discussed hereafter) and their relative scarcity (i.e. they represent a small area of the total Atlantic coastal zone).

Table 5.4 - Average Atlantic Coast unit ecosystem service values (ESV) per biome in the 2015, reference year (€/ha/year, 2015 price levels).

Biomes[1] \ Ecosystem Service[2]	**ESV_{Prov}**	**$ESV_{Reg\&Main}$**	**ESV_{Cult}**	**ESV_{Total}**
CSys	136.7	362.7	102.8	602.2
CWet	86.0	447.0	397.9	930.8
CuAr	374.8	146.6	0.0	521.4
Dser	9.3	0.0	102.8	112.2
FrWa	82.0	6.8	102.8	191.6
Gras	9.3	6.8	102.8	118.9
InWt	70.9	799.2	449.4	1319.5
TeFo	9.3	193.9	4.7	208.0
TrFo	54.0	75.0	340.5	469.5
Wood	9.3	6.8	102.8	118.9

Note: [1] *CSys* = Coastal System; *CWet* = Coastal Wetland; *CuAr* = Cultivated Area; *Dser* = Desert/Snow; *FrWa* = Fresh Water; *Gras* = Grassland; *InWt* = Inland Wetland; *TeFo* = Temp./Bor. Forest; *TrFo* = Tropical Forest; *Wood* = Woodland;

[2] ESV_{Prov} = Provisioning ecosystem service values; $ESV_{Reg\&Main}$ = Regulating & maintenance ecosystem service values; ESV_{Cult} = Cultural ecosystem service values; ESV_{Total} = Total ecosystem service values.

Note that these ESV suffer alterations for projections towards 2100, due to changes in socioeconomic conditions (as per Table 5.3) – *in* particular income and population density. The unit ecosystem service values for each country is shown in the Table 5.5 below.

Table 5.5 - Current ecosystem service values (ESV), in €/2015, and area at risk due Sea Level Rise by country.

Country/ Continent		**Coastal Area**	**ESV$_{\text{Prov}}$**	**ESV$_{\text{Reg\&Main}}$**	**ESV$_{\text{Cult}}$**	**Area in risk due SLR (%)**	
		10^6 ha	**Value in 10^6 €/2015**			**RCP 4.5**	**RCP 8.5**
Angola	Africa	16.9	225.4	50.1	493.6	0.2%	0.2%
Benin		1.5	44.0	1.5	5.6	2.6%	3.3%
Cameroon		5.2	248.0	41.8	139.0	0.0%	0.1%
Cape Verde		0.4	24.8	3.2	15.4	0.6%	0.8%
Congo, D. Rep.of		3.0	46.1	3.6	4.1	0.2%	0.2%
Congo, Rep. of		1.8	11.6	0.2	54.6	0.2%	0.2%
Eq. Guinea		1.9	467.3	17.5	2,721.4	0.1%	0.1%
Gabon		8.6	286.0	9.4	2,398.5	0.5%	0.6%
Gambia		1.0	59.3	37.6	23.0	2.9%	4.4%
Ghana		5.3	171.6	74.5	53.6	2.5%	2.9%
Guinea		4.1	11.6	2.5	43.2	0.7%	1.0%
Guinea-Bissau		3.2	51.9	10.6	31.5	0.3%	0.4%
Ivory Coast		6.1	84.0	51.2	85.3	1.3%	1.5%
Liberia		5.5	168.2	36.7	24.0	0.0%	0.0%
Mauritania		6.7	7.4	3.1	21.8	2.9%	3.0%
Morocco		14.7	122.4	15.7	346.7	0.1%	0.1%
Namibia		16.3	2.9	0.0	138.9	0.3%	0.3%
Nigeria		12.4	239.3	573.2	491.0	0.2%	0.3%
S. To. and Princ.		0.1	1.6	0.1	8.4	0.0%	0.0%
Senegal		8.0	147.0	44.6	247.5	3.6%	4.6%
Sierra Leone		4.1	87.1	48.6	27.7	0.5%	0.7%
South Africa		16.6	142.9	129.2	518.3	0.0%	0.1%
Togo		1.1	7.9	13.9	5.5	0.6%	0.7%
Wes. Sahara		10.7	45.1	0.2	176.5	0.2%	0.2%
Belize	Central Am.	2.5	45.2	3.0	83.5	3.8%	5.1%
Caribean Isl.		26.6	4,165.8	11,565.7	6,509.2	2.3%	3.1%
Costa Rica		2.8	134.7	171.2	2,274.8	0.1%	0.2%
Guatemala		1.9	56.6	22.7	171.2	0.8%	1.1%
Honduras		6.6	111.6	35.3	330.7	1.4%	1.9%
Nicaragua		5.5	16.4	15.6	171.2	2.2%	3.1%
Panama		6.7	612.9	379.3	4,774.8	0.6%	0.7%
Belgium	Europe	3.3	2,546.4	1,616.3	102.8	2.5%	2.7%
Denmark		8.2	2,478.5	4,940.1	199.5	4.4%	4.8%
Estonia		7.6	873.5	685.9	341.0	3.8%	4.7%
France		23.8	5,332.7	5,010.2	1,200.5	1.3%	1.6%
Germany		14.4	3,128.0	346.3	188.9	3.2%	3.7%
Ireland		12.4	509.8	5,056.1	3,556.5	0.9%	1.1%

Latvia		8.9	871.3	816.9	271.1	0.9%	0.9%
Lithuania		4.3	645.0	711.3	28.3	0.6%	0.6%
Netherlands		5.8	4,046.9	7,290.1	675.7	9.2%	10.2%
Norway		11.1	1,863.2	1,804.7	733.9	0.5%	0.6%
Poland		9.6	793.5	198.4	80.6	1.5%	1.5%
Portugal		9.7	1,580.6	1,998.1	1,496.6	0.6%	0.7%
Russia		8.0	1,088.6	638.0	76.7	3.4%	3.8%
Spain		16.3	1,186.1	2,879.9	2,919.4	0.3%	0.4%
Sweden		22.7	8,881.5	2,361.6	561.3	3.4%	4.1%
Un. Kingdom		44.1	3,561.9	2,763.3	5,344.7	0.9%	1.1%
Canada	North Am.	88.3	5,479.5	7,619.6	1,696.6	0.9%	1.1%
Mexico		30.1	1,965.3	8,261.6	680.8	4.9%	6.0%
Un. States of America		93.5	9,186.6	21,724.0	2,038.0	4.4%	5.6%
Argentina	South Am.	53.6	8,190.1	4,318.1	9,157.7	1.6%	2.0%
Brazil		101.5	11,555.0	486.0	31,563.2	1.9%	2.5%
Chile		11.7	1,983.5	422.7	9,242.3	2.2%	2.7%
Colombia		10.8	4,659.8	1,026.3	3,052.2	2.6%	3.4%
French Guiana		4.5	79.4	7.0	402.9	0.6%	0.8%
Guyana		7.5	223.2	48.1	546.5	1.5%	2.2%
Suriname		6.6	432.7	54.0	974.4	3.3%	4.4%
Uruguay		7.4	672.7	909.8	1,540.2	2.8%	3.3%
Venezuela		25.6	1,987.3	74.7	9,338.9	2.6%	3.4%

Note: [1] ESV_{Prov} = Provisioning ecosystem service values; $ESV_{Reg\&Main}$ = Regulating & maintenance ecosystem service values; ESV_{Cult} = Cultural ecosystem service values.

5.3.2. Risk of flood due sea-level rise

Figure 5.5 shows the results of the Uncertainty Bathtub Model (uBTM), where Figure 5a to 5c present the maps of the areas at risk of flood for RCP 4.5 by 2100 and Figure 5d to 5f present the maps of the areas at risk of flood for RCP 8.5 by 2100. The countries that present the largest area at risk of flood due to SLR in the Atlantic coastal zone are the Netherlands, with a risk of loss of 9.2%-10.2% (Figures 5c and 5f), and between Mexico and the United States, with a risk of loss between 4.9%-6.0% and 4.4%-5.6% respectively (Figures 5b and 5e). Note that other countries, such as Belize, Denmark and Estonia, have about 5.0% of their coast at risk in the worst-case scenario. More detailed information per country can be obtained from Table 5.5.

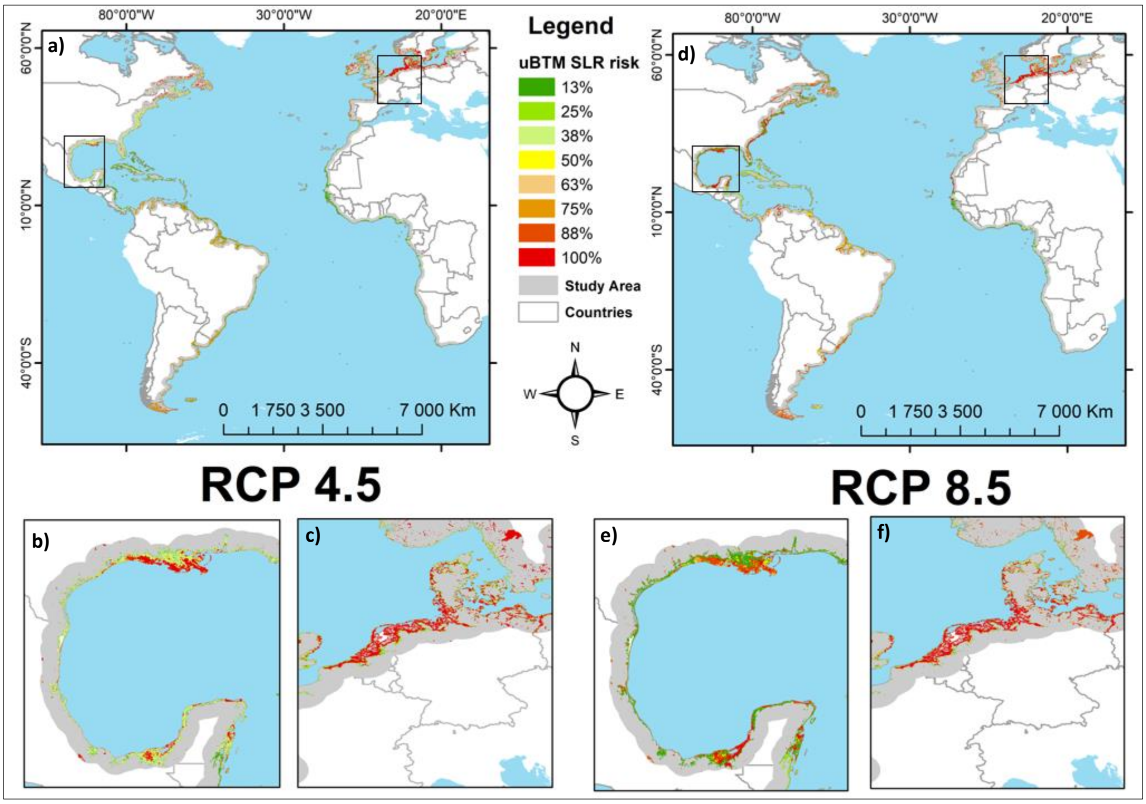

Figure 5.5 - Areas at risk of flood for RCP 4.5 (a) to c)) and RCP 8.5 (d) to f)) by 2100 (based on uBTM results).

Submergence probability is converted to the area at risk of flood due to SLR assuming direct proportionality. For example, an area of 100 ha with 25% risk would imply losing 25 ha and so on, according to each risk percentage. It is important to highlight that in this analysis, coastal erosion control structures were not considered, this would require more complex and detailed information. Figure 5.6 presents the summary of the coastal area and the percentage at risk of flood due to SLR with uBTM application by continent. The continent with the greatest SLR risk was North America, with the probability of losing an area greater than 7.63 million ha, approx. 3.6% of its coastal territory; then South America, 2.5%; Central America, 2.4%; Europe, 2.1%; and Africa, 0.8%, when analyzed the SLR risk for RCP 8.5 in 2100.

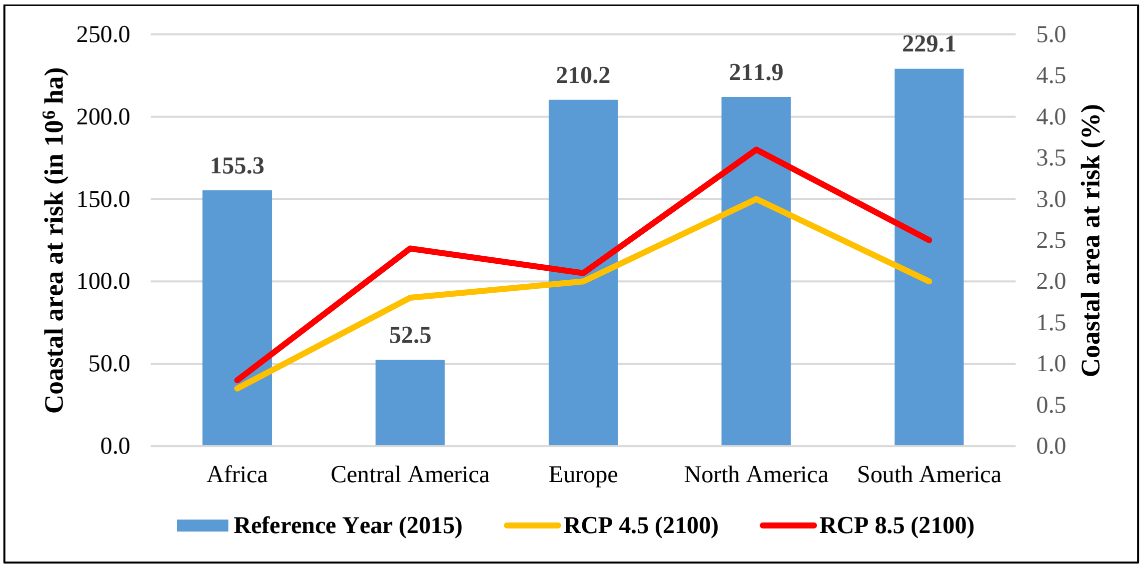

Figure 5.6 - Atlantic coastal zone area (in ha) and percentage (in %) at risk of flood due to sea-level rise per continent for Reference Year (blue, left axis), RCP 4.5 (orange, right axis) and RCP 8.5 (red; right axis) by 2100 (based on uBTM results).

Although the area at risk is small as compared to the entire Atlantic coastal zone, not exceeding more than 2.4% of the total area, the impacts are different for each coastal biome. Table 4.6 presents the area at risk of flood by biome in the Atlantic coastal zone, considering the RCP 4.5 and RCP 8.5. The biomes most affected are Fresh Waters and Coastal Wetlands with, respectively, 36.4% and 16.6% of the area at risk under RCP 8.5. These biomes are usually located in low altitude areas, and, because of that, they present direct contact with the ocean, being consequently disturbed by the flooding process. Li et al. (2020) highlight that those losses due to the flooding process will be irreversible, if the RCP 8.5 scenario occurs, with diverse impacts, such as vegetation die-back and increase in salinity due to direct tidal flushing.

Table 5.6 - Coastal land cover area for reference year (RY; in ha) and area at risk for RCP 4.5 and RCP 8.5 by 2100 (in ha; based on uBTM results).

Biome[1]	**Continental Area**	**Area at risk due to SLR**			
	RY (2015)	**RCP 4.5 (2100)**		**RCP 8.5 (2100)**	
	Area (10^6 ha)	Area (10^6 ha)	(%)	Area (10^6 ha)	(%)
CSys	105.9	0.95	0.9%	0.97	0.9%
CWet	2.8	0.13	4.5%	0.14	4.9%
CuAr	21.8	3.02	13.9%	3.61	16.6%

Dser	189.6	1.74	0.9%	1.90	1.0%
FrWa	38.6	0.23	0.6%	0.23	0.6%
Gras	26.1	8.20	31.4%	9.49	36.4%
InWt	14.8	0.54	3.7%	0.75	5.1%
TeFo	168.0	0.86	0.5%	1.03	0.6%
TrFo	138.8	0.55	0.4%	0.77	0.6%
Wood	135.2	0.80	0.6%	1.06	0.8%
UrbA	17.5	0.20	1.2%	0.24	1.3%

Note: [1] *CSys* = Coastal System; *CWet* = Coastal Wetland; *CuAr* = Cultivated Area; *Dser* = Desert/Snow; *FrWa* = Fresh Water; *Gras* = Grassland; *InWt* = Inland Wetland; *TeFo* = Temp./Bor. Forest; *TrFo* = Tropical Forest; *Wood* = Woodland; *UrbA* = Urban Area.

5.3.3. Ecosystem service values lost

As a result of the joint analysis between the RCP and SSP, it was possible to estimate future risk of SLR by scenario for the year 2100. In this analysis, the continental values are differentiated by ecosystem service for the reference year (2015; see Figure 5.7) and for the ESV at risk according to the scenarios (for 2100; see Figure 4.8). An issue worth mentioning is the general comparison between the values in the reference year and those in the future scenarios. The values in the risk of flood scenarios are based on data for the year 2100, for which a relative increase is observed for the socioeconomic variables that were applied in the meta-analytic value functions, in particular population and income.

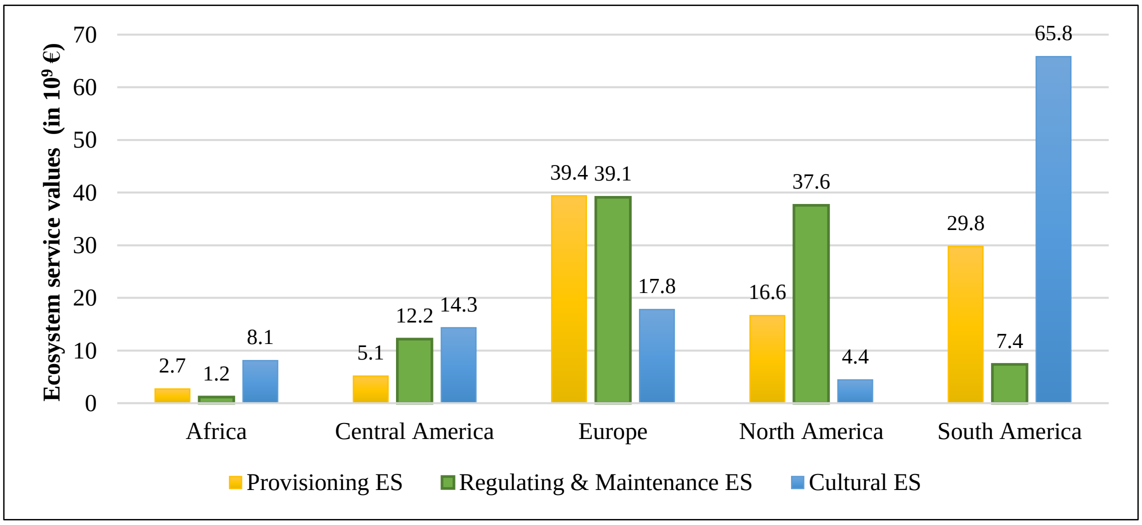

Figure 5.7 Provisioning, Regulating & maintenance and Cultural ecosystem service values (ESV) for the Atlantic Coastal Zone per continent in the 2015 reference year (in 10^9 €/year; 2015 price levels).

In the reference year (2015), the continental coast with the highest Provisioning ESV are in Europe, 39.4 € billion/year, while the lowest are in Africa, 2.7 € billion/year (see Figure 5.7). The same is observed for Regulating & maintenance ESV; the continent with the highest values are in Europe, 39.1 € billion/year, and the lowest are in Africa, 1.2 € billion/year. For Cultural ESV, however, the continent with the highest ESV are in South America, 65.8 € billion/year, and the lowest values are in North America, 4.4 € billion/year.

With the aim to assess the main continents that present their ESV at risk of flood due to the SLR process, we present an analysis segmented by type of ecosystem service. Figure 5.8 shows the change in ESV by RCP and SSP scenario (with the highest value SSP scenario highlighted above each value bar) for each continent. Note that there is variability between the values, mainly due to changes in socioeconomic data (such as *GNI* and *PDen*), which have therefore been converted into different values at risk of flood. The value of each scenario by continent is verify in Table 5.7.

Table 5.7 - Summary of ESV's at risk due Sea Level Rise by continent (in 10^9 €).

Continent	**ESV[1]**	**Future scenarios at risk due SLR[2]**					
	RY	**RCP 4.5 (2100)**			**RCP 8.5 (2100)**		
	(2015)	**SSP1**	**SSP2**	**SSP4**	**SSP2**	**SSP3**	**SSP5**
Provisioning Services Values							
Africa	2.70	0.11	0.13	0.02	0.16	0.02	0.22
Central America	5.14	0.15	0.12	0.24	0.16	0.08	0.29
Europe	39.39	2.92	2.83	2.54	2.74	1.60	5.88
North America	16.63	4.33	1.42	1.67	1.69	1.21	4.30
South America	29.78	6.74	2.07	3.44	2.58	1.29	5.17
Regulating & Maintenance Services Values							
Africa	1.17	0.03	0.05	0.05	0.07	0.07	0.11
Central America	12.19	0.85	0.84	0.62	1.14	0.87	1.20
Europe	39.12	0.66	2.14	1.99	1.83	1.27	2.75
North America	37.61	4.86	3.45	3.30	4.11	3.15	6.03
South America	7.35	1.49	0.99	0.77	1.23	0.95	1.56
Cultural Services Values							
Africa	8.08	1.61	1.25	0.26	1.57	0.43	3.50
Central America	14.32	1.38	1.14	0.85	1.54	0.76	2.80
Europe	17.78	1.34	1.64	1.68	1.74	1.04	3.18
North America	4.42	1.99	1.51	1.63	1.75	1.03	3.52
South America	65.82	15.61	8.00	6.97	10.15	5.02	21.33

Note: [1] Ecosystem Service Values consider in the Reference Year (2015); [2] Ecosystem Service Values at risk due SLR consider the Future (2100).

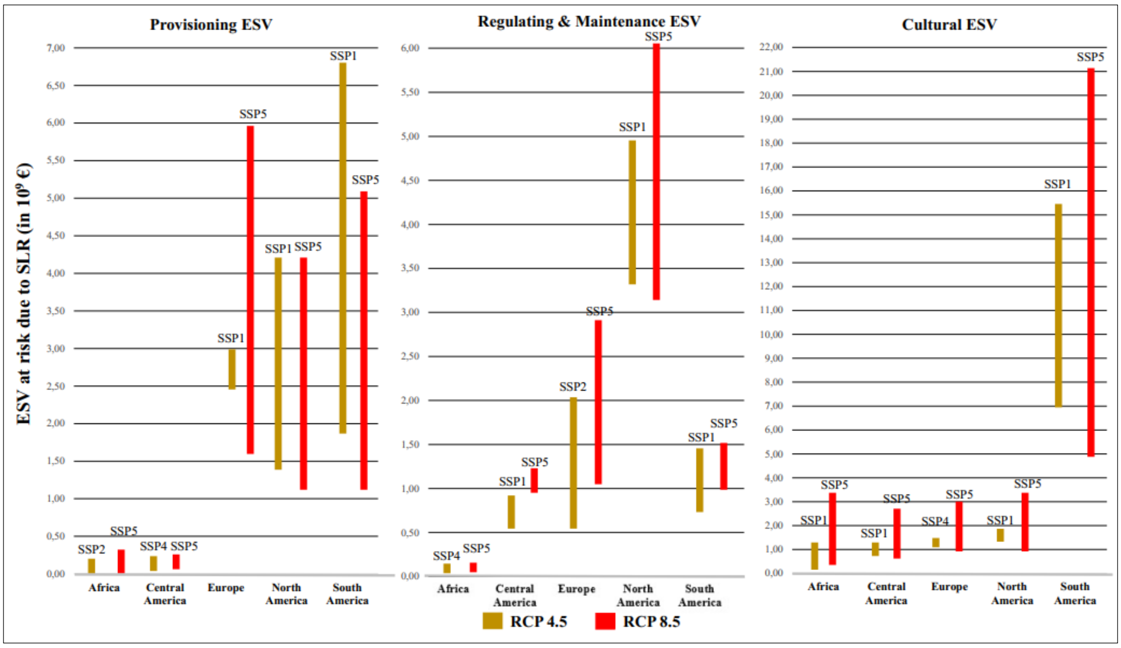

Figure 5.8 - Ecosystem service values (ESV) at risk of flood due to sea-level rise by RCP and SSP scenario for each continent by 2100 (in 10^9 €/year; 2015 price levels).

The RCP 4.5 represents a scenario with slowly declining emissions, hence aligning with those SSP that have least challenges for mitigation (SSP1, SSP2 and SSP4). When examining this future scenario (2100), the coastal zone with the highest probable losses in Provisioning ESV is in the SSP1 scenario for South America, 6.74 € billion/year. For Regulating & maintenance ESV, the scenario with the highest probable losses is the SSP1 for North America, 4.86 € billion/year. For Cultural ESV, the scenario with the highest probable losses is the SSP1 for South America, 15.61 € billion/year. Note that the major values at risk, are associated with the SSP1 scenario, presenting, among other characteristics, emphasis on human well-being and environmentally friendly technologies and renewable energy. The SSP1 is the scenario adopted jointly with RCP 4.5, which presented the greatest increase in income, and therefore presented the highest ES values, consequently the greatest associated losses.

On the other hand, the RCP 8.5 represents a high-end scenario with rising emissions, hence aligning with those SSP that face the largest challenges for mitigation (SSP2, SSP3 and SSP5). The largest losses in RCP 8.5 are associated with the SSP5 scenario, which presents, among other characteristics, global adoption of resource and energy-intensive lifestyles and emphasis on economic growth and technological progress. In fact, among all SSP, this is the one with the greatest increase in income, which is directly associated with the global ecosystem service value functions. Analyzing this future scenario (2100), the coastal zone with the highest probable Provisioning ESV losses is in the SSP5 scenario for Europe, 5.88 € billion/year. For Regulating & maintenance ESV, the scenario with the highest probable losses is the SSP5 for North America coast, 6.03 € billion/year. For Cultural ESV, the scenario with the highest probable losses is the SSP5 for South America, 21.33 € billion/year.

Seeking to observe the main countries that have their ESV at risk of flood, we present below an analysis segmented by ecosystem service and sea-level rise scenarios. Results are presented in percentage terms, emphasizing potential flood losses due to SLR, and summarizing for the scenarios RCP 4.5 and RCP 8.5. Figure 5.9 shows the potential ESV losses due to SLR for RCP 4.5 and, which presents the percentage losses for taking into account the SSP1, SSP2 or SSP4; similarly, Figure 5.10 shows those for RCP 8.5, which presents the percentage losses for taking into account the SSP2, SSP3 or SSP5.

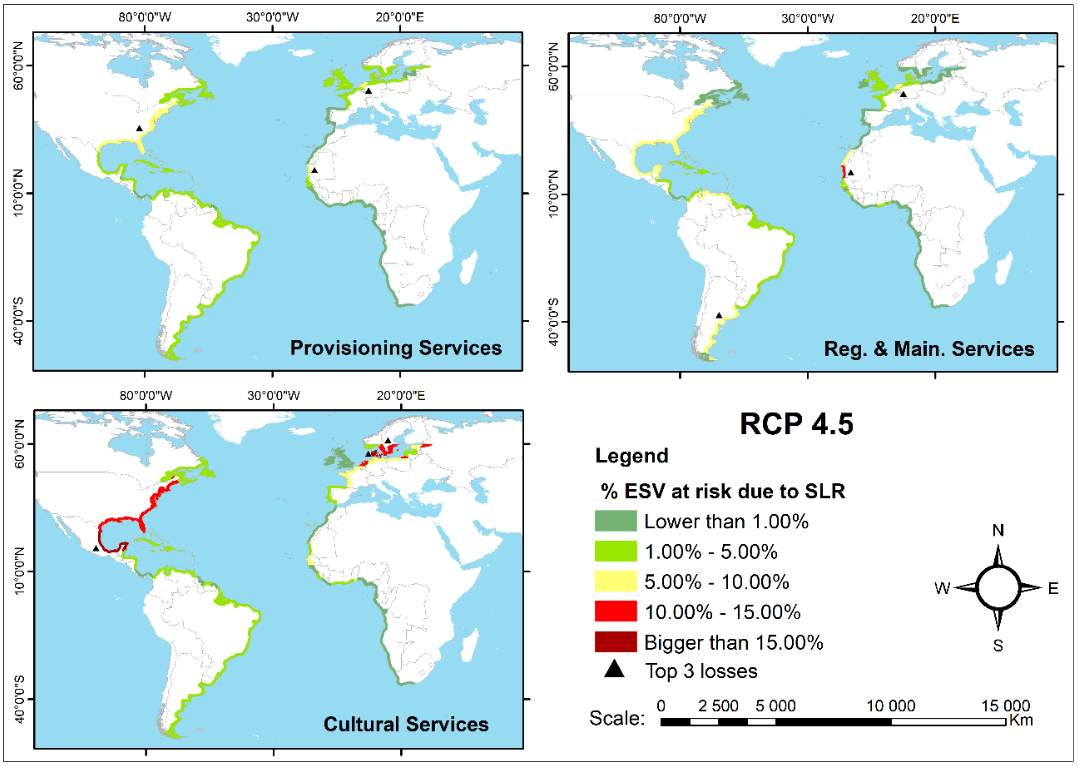

Figure 5.9 - Potential ecosystem service values (ESV) at risk due to sea-level rise for RCP 4.5 by 2100.

For RCP 4.5, by 2100, the countries at potential risk of losing Provisioning ESV are the Netherlands (7.9%), United States (6.2%), and Mauritania (5.3%). For Regulating & maintenance ESV, the top 3 countries impacted are Mauritania (13.9%); the Netherlands (7.5%), and Argentina (6.6%). For Cultural ESV, the countries are Denmark (17.4%), Mexico (16.6%), and Sweden (13.5%).

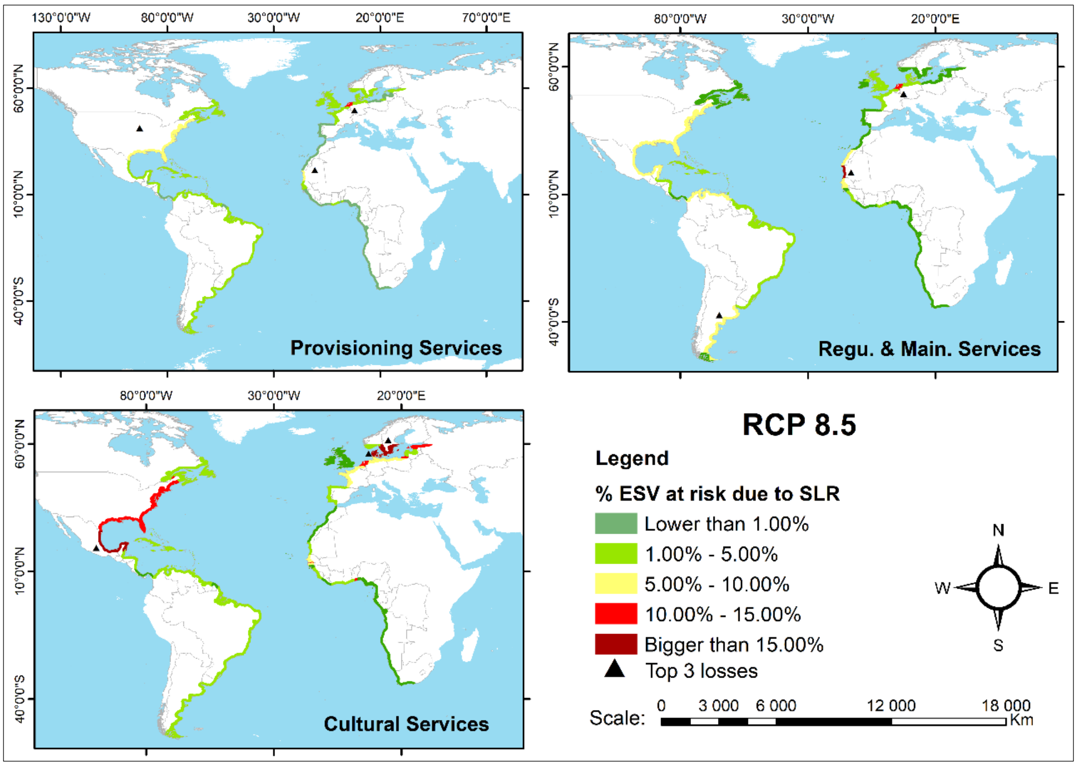

Figure 5.10 - Potential ecosystem service values losses due to sea-level rise RCP 8.5 by 2100.

For RCP 8.5, by 2100, the countries facing highest relative risk of losing Provisioning ESV are the Netherlands (10.6%), United States (7.4%) and Mauritania (5.8%). For Regulating & maintenance ESV, the top 3 countries impacted are Mauritania (17.6%), the Netherlands (10.0%) and Argentina (8.0%). For Cultural ESV, the countries are Mexico (19.0%), Denmark (18.1%) and Sweden (15.6%). Hence, the list of countries is not modified, however, an increase in the potential ESV losses is observed.

In general, the main potential flood losses due to SLR are distributed across all continents along the Atlantic coastal zone. The continent least impacted is Central America, which does not configure any country among the most impacted countries, which means they are not in the "Top 3" losses of each service evaluated. Another point to be noted is that the northern European countries are among the most impacted, mainly the Netherlands, Denmark and Sweden, in these countries the risk of flood is higher and consequently the ESV losses are larger. Among the ESV analyzed, the greatest losses are observed for Cultural services. This mainly because Cultural ESV are linked to coastal ecosystems, such as wetlands (coastal/inland) and coral reefs, which have a high value in the Cultural ESV model.

5.4. Discussion

5.4.1. Comparison with other studies

Our results can be compared with those from similar previous studies, performed for the world (Martinez et al., 2007) and European (Roebeling et al., 2013; Paptrony et al., 2021) coastal zones (see Table 5.8). Average unit ecosystem service values in these studies, across all types of ecosystem services and all types of biomes, varies between 86.9 and 8,378.5 €/ha/year. Lowest unit ecosystem service values are observed in Martinez et al. (2007), as their coastal zone is delimited by a 100 km buffer (thus including a larger share of ecosystem services with lower unit value; such as grassland and desert/snow areas) and for the world (thus including a larger share of low unit value desert/snow areas around the tropics and the polar regions). Highest unit ecosystem service values are observed in Paptrony et al. (2021), who not only use a coastal zone delimited by a 10 km buffer (thus including a larger share of near-coast ecosystem services with high unit value; such as Coastal Systems and Coastal Wetlands) but also adopt values for Urban Systems (with high unit value). Our study points to comparatively low average unit ecosystem service values (351.0 €/ha/year), as it uses a coastal zone delimited by a 100 km buffer (thus including a larger share of ecosystem services with lower unit value), it is a study for the Atlantic coastal zone (thus also including the tropics areas), and it does not include values for Urban Systems. In addition, it uses value function transfer rather than unit value transfer – where the former is argued to be preferred (i.e. leads to lower transfer errors) when transferring across sites that are relatively dissimilar and where the latter is argued to be preferred when transferring across sites that are relatively similar (see e.g. Lindhjem & Navrud, 2008; Bateman et al., 2011). Reynaud & Lanzanova (2017) point-out some of the challenges of meta-analysis and value function transfer when working at the global scale, associated with cultural or societal differences, the under-representation of some regions and the aggregation of individual benefits. When contextualized for differences in methods and geographic scope, the ES values obtained in this study are well within the ranges found in the literature.

Table 5.8 - Average unit (in €/ha/year) and total (€/year) ecosystem service values (ESV) for studies analyzing coastal ecosystem services (2015 price levels).

Authors	Location	Year of study	Area (10^6 ha)	ESV_{Total} (10^9 €/year)	ESV (€/ha/year)
Martinez et al. (2007)	World coast	1992	1,819.9	158.2	86.9
Roebeling et al. (2013)	European coast	2006	21.7	21.0	969.7
Paptrony et al. (2021)	European coast	2018	58.0	485.7	8,378.5
This study	Atlantic coast	2015	859.0	301.5	351.0

Two of these studies assess, for the European coastal zone, the impacts of climate change and sea-level rise in the coastal area and ecosystem service values at risk (Roebeling et al., 2013; Paptrony et al., 2021; see Table 5.9). Roebeling et al. (2013) do so for projections until 2050, using the IPCC-SRES scenarios B1 (lower-bound, with an emphasis on a world more integrated and more ecologically friendly) and A1F (upper-bound, with an emphasis on fossil-fuels and rapid economic growth; Nakicenovic and Swart 2000). The SRES scenarios were superseded by the RCP scenarios in the IPCC fifth assessment report in 2014 (Riahi et al., 2017). Paptrony et al. (2021), and also our study, perform projections until 2100, using the scenarios RCP 4.5 (without overshoot pathway to 4.5 W/m^2 in radiative forcing and stabilization after 2100) and RCP 8.5 (with an increasing radiative forcing pathway leading to 8.5 W/m^2 by 2100).

Table 5.9 - Climate change scenarios and impacts (area and ecosystem service values [ESV] at risk) for studies analyzing coastal ecosystem services.

Authors	**Location**	**Climate change scenario (year projected)**	**Area at risk (%)**	**ESV at risk (%)**
Roebeling et al. (2013)	European coast	SRES B1 (2050)	1.8%	6.9%
		SRES A1F (2050)	2.7%	10.1%
Paptrony et al. (2021)	European coast	RCP 4.5 (2100)	0.7%	4.2% [3.0–6.1 %]
		RCP 8.5 (2100)	2.2%	5.1% [3.3–8.5 %]
This study	Atlantic coast	RCP 4.5 and SSP1 (2100)	2.0%	2.3%
		RCP 4.5 and SSP2 (2100)		2.5%
		RCP 4.5 and SSP4 (2100)		2.5%
		RCP 8.5 and SSP2 (2100)	2.4%	2.8%
		RCP 8.5 and SSP3 (2100)		2.9%
		RCP 8.5 and SSP5 (2100)		3.2%

Although the study locations, climate change scenarios and year projected are different between these studies (see Table 7), the area at risk due to SLR does not differ much – varying between 0.66 - 2.68% of the coastal area. For the same RCP scenarios and year (2100), our estimates are higher for RCP 4.5 (2.0% vs. 0.7%) or similar for RCP 8.5 (2.4% vs. 2.2%) to those from Paptrony et al. (2021). The estimated areas at risk until 2050 by Roebeling et al. (2012) are above (considering the projected year) those from Paptrony et al. (2021) and our study. Considering the ecosystem service values at risk (Table 7), our estimates are well below those from Roebeling et al. (2012) and somewhat below those from Paptrony et al. (2021), given the larger estimated area at risk and/or used unit ecosystem service values.

5.4.2. Limitations

The land cover used in this study was the CCI-LC, a worldwide database with 300m resolution and often too low to capture important aspects of the coastal zones. Moreover, CCI-LC was designed to be used across world regions and not explicitly designed to account for the characteristics of any country or biome. Further, it was necessary to adapt between the different classes, being necessary to reclassify the land cover for an approximation to the biomes used in the global ecosystem service value functions.

However alternatives are scarce and CCI-LC is currently one of the most comprehensive datasets of its kind available worldwide.

According to Paprotny et al. (2021), one of the most important sources of uncertainty is related to coastal processes, which becomes even more pronounced when we evaluate phenomena related to climate change, such as sea-level rise. This is challenging at a multi-continental scale and implies some limitations due to the lack of data, predictive tools, and the availability of computational resources. The CoastalDEM dataset used in this study, which presents sensing data of 90 m with a vertical error of 2.5 m, may be too coarse for parts of the Atlantic coastal zone. The Uncertainty Bathtub Model applied a probabilistic form related to uncertainties (see de Lima et al., 2021). These percentages present the risk of an area being flooded and, therefore, they will not necessarily be affected by SLR. Hence, in this study the percentage risk was used as a weighing factor.

Uncertainties are also nested in the economic analysis. Ecosystem services have a specific value and are measurable, but there is great diversity in methods used to estimate their actual value (for an overview, see Portman, 2013; Solé & Ariza, 2019). Ecosystem service value function transfer reduces these errors, considering local specifications to determine ESV; several studies used meta-analytic function transfer for the valuation of ecosystem services (Hjerpe et al., 2015; Rao et al., 2015; Hynes et al., 2018). Magalhães Filho et al. (2021) showed that the application of meta-analytic function transfer provides ESV with more accuracy than unadjusted unit value transfer, by using local variables, such as income, population, and share of agricultural and forest area. However, the values adopted for the variables refer to a national average while several regions in a country may present unique characteristics – in particular for countries with great area extension, such as Canada, the United States and Brazil. In addition, we seek to aggregate ES into 3 main types: Provisioning, Regulating & maintenance and Cultural services, which could easily be subdivided into many others (see e.g. de Groot et al., 2012; Costanza et al., 2014).

Due to flooding processes, the supply of ES is, as shown, unlikely to increase in the Atlantic coastal zone. However, demand for ES could change due to factors such as an evolution in preferences or willingness-to-pay (Costanza, 2000; Uehara et al., 2018). Such preferences are complex and very uncertain, and the absolute value of ESV losses could be affected. However, this effect also comes from price inflation, general economic shifts or movements in exchange rates between countries. The SSP scenarios show there is an increase in income for practically all future scenarios associated with the increase in world wealth, due to factors such as technological progress and increases in productivity.

Among the limitations observed in this study, we underline the focus on flooding and, thus, not measuring other physical factors such as coastal erosion of areas. Coastal erosion could be compensated in some locations with land accretion (Ratliff & Murray, 2014), while it is uncertain what ecosystem would develop in this accretion area and in what timeframe. For example, for wetlands, the main affected biome, it is difficult to infer what types of biophysical transformations will occur and whether the biomes will migrate to other areas, transform into another, or be submerged (Hussain et al., 2019). Additionally, this study did not consider extreme sea-level episodes, such as storms, high tides and hurricanes, which may cause permanent flooding or the loss of protective habitats (Paprotny et al., 2021; Vousdoukas et al., 2020).

The impact of the damage on coastal ecosystems is considered linear (i.e. proportional to the area flooded), but this may perhaps not be the case because of the complexity of the natural environment (Barbier et al., 2008; Paprotny et al., 2021). A non-linear association between ecological features and ecosystem services have only been investigated at local scales, and due to its complexity and scale of analysis (the entire Atlantic coastal zone) this is not feasible (Aburto-Oropeza et al., 2008).

Besides changes in socioeconomic conditions, there are other factors, such as changes in land cover and use caused by human activities, especially associated with the expansion of urban, industrial and infrastructure-related areas. Such projections are under development for urban, agricultural and forest land uses mainly at the local/national/regional scale (see e.g. Schaldach et al., 2006; Verburg & Overmars, 2009; van Vuuren et al., 2011; Van Asselen, S. & Verburg, 2013).

We acknowledge that the RCP and SSP scenarios might not necessarily span the full range of possibilities (Hinkel et al., 2021). Alternative socioeconomic scenarios point towards both a higher and lower population in 2100 than that used in the SSP scenarios (Vollset et al., 2020). Likewise, some authors argue that there is a 35% chance of exceeding RCP 8.5 (Christensen et al., 2018), while others argue that RCP 8.5 is an extreme and very unlikely scenario (Hausfather & Peters, 2020).

5.5. Conclusions

This study analyzed the effects of flooding due to sea-level rise on future ecosystem services and values in the Atlantic coastal zone. The integration of methodologies with the Uncertainty Bathtub Model (uBTM; for the creation of alternative flood probability maps), ecosystem services valuation (using meta-analytic based global value functions), and RCP climate and SSP socioeconomic scenarios (for 2100), allowed to verify the likely continents and countries as well as ecosystem services and values most affected by sea-level rise. This study goes beyond previous studies by using meta-analytic function transfer (rather than unit value transfer), combinations of climate change and socioeconomic scenarios (rather than climate change scenarios, only) and, finally, applying the analysis to 5 continents (rather than Europe, only).

Despite the large uncertainty in the scenarios, associated with analyzing the year 2100, there are two trends in the projections presented here. The first is related to the risk of flooding of land territories due to the SLR process, with around 2.4% of the Atlantic coastal zone area at risk of flood. Some countries face up to 4.5% of their coastal zone area to be affected by flooding, namely they Netherlands, Mexico, United States of America, Belize, Denmark and Estonia. The second is the influence of local factors, such as population and income, on future ecosystem service values. As demonstrated, there is an expected increase in population and income in the future (2100) that, although generating an increase in ecosystem service values, also emphasizes that these values will be at risk. Thus, sea-level rise and socioeconomic changes impact ecosystem services and values – directly affecting the well-being of the world population.

Results show that the set of scenarios that generate the greatest potential of ecosystem service values (ESV) at risk, are related to the occurrence of RCP 8.5 together with SSP5 – i.e. the worst-case scenarios with a narrative related to fossil-fueled development. For this scenario, by 2100, the coastal zone with the highest probable losses in Provisioning ESV is Europe (~5.9 € billion/year), for Regulating & maintenance ESV this is North America (~6.0 € billion/year) and for Cultural ESV this is South America (~21.3 € billion/year). Countries facing highest relative risk of losing Provisioning ESV are the Netherlands (~11%), United States (~7%) and Mauritania (~6%). For Regulating & maintenance ESV, the relative most impacted countries are Mauritania (~18%), the

Netherlands (~10%) and Argentina (~8%). For Cultural ESV, the countries are Mexico (~19%), Denmark (~18%) and Sweden (~16%).

Ecosystem service value changes are exponentially related to flood risk and economic growth, such that small changes in flood or income lead to large changes in ESV. Unlike previous studies (see e.g. Martinez et al., 2007; Roebeling et al. 2013; Paprotny et al., 2021), the ESV established in this study are dependent on time and local conditions, such as population and income for reference and future scenarios. As an increase in population and income is expected in the future (2100), thus generating an increase in ESV, it emphasizes the ecosystem service values at risk.

Insight in the distribution of coastal ecosystem service values across continents and countries, is important to identify what values are at risk and for whom. Global changes, such as population growth, economic development and climate change, put pressure over these coastal ecosystem service values and, hence, it can be assessed what biomes, services, countries and continents are mostly affected by climate change, sea level rise and flooding. Adaptation measures and strategies can, in turn, be defined.

Finally, the perception of the importance of human, social and built as well as natural capital services and values are crucial in the development of coastal adaptation strategies. Coastal adaptation strategies should be based on full welfare analyses that considers human, social and built as well as natural capital services and values. This study helps as a warning, indicating regions in the Atlantic coastal zone that may suffer, more severely, with the sea level rise process, and can therefore support coastal protection planning assisting adaptation strategies.

CHAPTER 6

6. Conclusions and final remarks

This chapter provides an overview of the objective(s), approach and contributions to current state of knowledge (Section 6.1), the main results (Section 6.2), overall conclusions (Section 6.3), policy implications (Section 6.4) and, finally, caveats and future research recommendations (Section 6.5).

6.1. Objective(s), approach and contributions to current state of knowledge

The overall objective of the present study was to determine the value of coastal ecosystem services in the face of global change, through meta-analytic function transfer, analyzing land use and socio-economic changes over the years (2005-2015), and assessing the values at risk due to future changes in climate, sea level and socio-economic conditions (by 2100). A case study was provided for countries on the Atlantic Coastal zone.

To this end, first key anthropogenic and natural factors that influence the rate of coastline retreat were assessed, based on historical data and using correlation and regression analysis. Second, meta-analytic value functions for 3 ecosystem services across 12 biomes were estimated, based on primary and complementary data and performing a meta-analysis. Third, the values provided by ecosystem services in the Atlantic coastal zone over the period 2005–2015 were mapped and assessed, based on land use and socio-economic data and using meta-analytic function transfer. Finally, the joint impact of flooding and socioeconomic development on the future ecosystem services and values in the Atlantic coastal zone by 2100 were analyzed, based on flood probability maps and climate and socio-economic scenarios and using meta-analytic function transfer.

This thesis contributes to the current state of knowledge in various ways. First, correlation and regression analysis based on historical data, allows to assess the key anthropogenic and natural factors that influence the rate of coastline retreat. Second, meta-analytic ecosystem service value functions were estimated for 3 ecosystem services across 12 biomes, allowing for the estimation of ecosystem service values that consider the local context of the country and area under analysis and, thus, reducing value transfer errors. Third, meta-analytic ecosystem service value function transfer in combination with historical land use and socio-economic data, allows for the historical assessment of the evolution of ecosystem service values across time and space. Finally, meta-analytic ecosystem service value function transfer in combination with future climate, sea-level and socio-economic conditions, allows for the future assessment of the evolution of ecosystem service values across time and space in the face of global change.

6.2. Main results

The thesis was developed by chapters, except for the **Introduction** that delivers the foreword about coastal ecosystems and climate changes, dealing with specific subjects that are interconnected with the thesis premise. For that reason, the next paragraphs provide an overview of each Chapter.

Chapter 2 assessed the influence of anthropogenic and natural factors on coastline retreat in Vagueira Beach (Central Portugal), by the correlation and multiple linear regression analyses of coastline retreat in Vagueira Beach with the total length of groins, annual dredging, and, to a minor extent, storm events. Through the temporal distribution of several factors in the analysis it can be concluded that coastline retreat in Vagueira Beach has increased and is expected to maintain this trend soon if no other mitigation measures are considered. In particular, this is observed because of the groins constructed along the coastal stretch north of Vagueira Beach and the volume of material dredged at the Aveiro Port entrance, which show an increasing trend. In addition, climate change is expected to lead to an increase in storm events over the next century. Hence, construction of groins along the coastal stretch north of Vagueira Beach should be carefully de-liberated, while recharge of the material dredged at the Aveiro Port entrance to beaches located south of it may be considered and are increasingly being considered to mitigate coastal erosion on this coastal stretch. In the meantime, local solutions in front of Vagueira Beach are assessed to halt and reverse coastline retreat in Vagueira Beach.

In **Chapter 3**, meta-analytic ecosystem service value functions were estimated as to assess the monetary values of ecosystem services that take into account the local context of the country and area under analysis. We estimated meta-regression functions for three types of ecosystem services (Provisioning; Regulating & maintenance; Cultural) and 12 types of land cover (Coastal systems; Coastal wetlands; Coral reefs; Cultivated areas; Desert; Fresh water; Grasslands; Inland Wetlands; Open Ocean; Temperate/Boreal Forests; Tropical Forests; Woodlands). Results show that the highest ES values were those associated with Cultural services, followed by Regulating & maintenance and, finally, Provisioning services. Among the biomes with greater associated ecosystem service values are Coral reefs, Inland wetlands, and Coastal wetlands that are scarce and provide a great diversity of services. Thus, it was concluded that when taking into account the characteristics of the study area under analysis, including explanatory variables such as income, population density, and protection status, we can determine the value of ecosystem services with greater accuracy.

Chapter 4 presented a global ecosystem service value function application to map and assess the ecosystem service values associated with Provisioning, Regulating & maintenance and Cultural ecosystem services for the Atlantic coastal zone. Results show that, although there was a decrease in natural areas along the Atlantic coastal zone over the period 2005-2015, the ESV increased over time, mainly due to the increase in population density and income. The economic value of ES along the Atlantic coastal zone increased by 21%, from 585 billion to 710 billion €/year between 2005-2015. Tropical forests have been the highest appreciated biome, valuing 177-234 billion €/year over this period. Across the considered continents, the largest total ecosystem service value (ESV_{Total}) was found for Latin America & Caribbean, mainly due to the high value associated with Cultural services. Lowest ESV_{Total} were found for Africa, due to its lower population density and income and, also, the relatively large presence of low-value biomes such as Deserts.

Chapter 5 analyzed the effects of flooding due to sea-level rise and socio-economic development on future ecosystem services and values in the Atlantic coastal zone. The integration of methodologies with the Uncertainty Bathtub Model (uBTM; for the creation of alternative flood probability maps), ecosystem services valuation (using meta-analytic function transfer), and RCP climate and SSP socioeconomic scenarios (for 2100), allowed to verify the likely continents and countries as well as ecosystem service and values most affected by global change. Regardless of the large uncertainty in the scenarios, associated with analyzing the year 2100, there are two trends in the projections presented here. The first is related to the risk of flooding of land territories due to the SLR process, with around 2.0% of the Atlantic coastal zone area at risk of flood. Some countries face up to 4.5% of their coastal zone area to be affected by flooding, namely they Netherlands, Mexico, United States of America, Belize, Denmark and Estonia. The second is the influence of local factors, such as population and income, on future ecosystem service values. As demonstrated across the study, there is an expected increase in population and income in the future (2100) that, although generating an increase in ecosystem service values, also emphasizes that these values are at risk. According to the results, the set of scenarios that generate the greatest potential of ecosystem service values (ESV) at risk, are related to the occurrence of RCP 8.5 together with SSP5, i.e. the worst-case scenarios with a narrative related to fossil-fueled development. For this scenario, by 2100, the coastal zone with the highest probable losses in Provisioning ESV is for Europe (5.88 € billion/year), in Regulating & maintenance ESV is for North America (6.03 € billion/year) and in Cultural ESV is for South America (21.33 € billion/year). Countries at largest relative risk of losing Provisioning ESV are the Netherlands (10.6%), United States (7.4%), and Mauritania (5.8%). For Regulating & maintenance ESV, the top 3 of relatively most impacted countries are Mauritania (17.6%), the Netherlands (10.0%), and Argentina (8.0%). For Cultural ESV, the countries are Mexico (19.0%), Denmark (18.1%), and Sweden (15.6%).

6.3. Overall conclusions

Based on an assessment of the overall thesis, the following overarching lessons are learned. In the methodological process, it was possible to observe the following: i) The Necessity of an integrated approach that links meta-analytic function transfer, flood probability maps, and climate change and socio-economic scenarios, making it possible to analyze the effects of global change on future ecosystem services and values in the Atlantic coastal zone; ii) Importance of back- and forecasting, to understand the evolution process of the ES values as well as their determinant variables to provide information for decision making processes; iii) Necessity to validated data, information and scenarios (scales; uncertainties; historical data series) for better acceptance of methodological approaches used by the scientific community and policy makers; iv) Importance of model validation (Meta-regression models; benefit/value transfer methods; Uncertainty Bathtub Model) and sensitivity analysis, to prove the applicability of the proposed methodologies; and, finally, v) ESV as a function of explanatory variables, such as income and population, imply increases in ESV despite loss in ecosystem services supply.

Through the application of the thesis, it was possible to observe the following: i) Relative importance of ESV across types, biomes and continents/countries in Atlantic Coastal Zone; ii) Insight in historical changes in ESV across the Atlantic Coastal Zone; iii) Insight into those biomes and ESV at threat of sea level rise and socioeconomic changes across the Atlantic Coastal Zone; iv) Future narrative of possible ESV evolutions.

6.4. Policy implications

The supply of ES is critical to human wellbeing, they are essential to change the way societies manage the common natural capital in a more effective and sustainable way. As shown throughout this thesis, ecosystem service valuation, mapping and assessment helps decision makers to adequately balance the benefits of protecting natural ecosystems against the benefits of developing a region and the costs of recovering ecosystems from transformation, degradation and exploitation.

Most ES are either undervalued or have no direct value in the current decision-making processes, although crucial to human well-being. For the most part, policy decision-making processes take account of only traded goods and services. The valuation of benefits enables decision-makers to place a value on changes in services that are not captured only by markets. This is important because the ES concept is not fully incorporated in policies yet, although it is gradually becoming more integrated, particularly in policies governing natural ecosystems (Brouwma, et al. 2018; ICZM, Directive 2002/413/EC; MSFD; Directive 2008/56/EC).

Furthermore, to decrease the degradation of coastal natural capital, the support of ecosystem conservation policies and the improvement of the way resources are used are crucial to achieving sustainability. Estimates of coastal ES values, expressed in this thesis, are essential to growing awareness in societies about the importance of these services provided by natural capital relative to other services, such as those provided by built capital. Previous studies are based on unit value transfer and, thus, do not consider local characteristics, such as ecosystem location/accessibility, quality, territorial extension and socio-cultural dimensions, which are essential when estimating ecosystem service values. Understanding the distribution of coastal ES and values across types of services and biomes as well as countries and continents, as provided in this thesis, is crucial to recognize what values are at concern and for whom, in particular in the context of the increasing need for equitable distribution of benefits. Global changes, such as population growth, economic development and climate change, put pressure over these coastal ES and values and, hence, it can be assessed what services, biomes, countries and continents are mostly affected.

Coastal adaptation strategies, including retreat, accommodation, and protection measures, should be based on an integrated welfare analyses that consider human, social and built as well as natural capital services and values (Bosello et al., 2007). This will, for example, lead to coastal adaptation strategies that not only protect the traditional human, social and built capital services and values, but also, natural capital services and values.

6.5. Caveats and future research recommendations

Meta-analytic function transfer reduces value transfer errors by taking into account local specifications to determine ESV's. There are several studies that have used meta-models for the valuation of specific ecosystem services and biomes (e.g., Van Houtven et al., 2007; Hjerpe et al., 2015; Hynes et al., 2018), however, we have not found such a comprehensive study in the literature that has determined the value of 3 ecosystem services for 12 different biomes in the world. Even considering that there are transfer errors with the application of meta-analytic function transfer, as compared to other benefit transfer techniques (such as unit value transfer), meta-analytic function transfer has shown to provide better estimates for valuation of ecosystem services.

Some caveats remain. First, we used a meta-analysis, which is based on data from the Ecosystem Service Valuation Database (ESVD, 2020) that includes more than 320 studies published until 2009. Since then, numerous primary valuation studies have been developed – as evidenced by the recently updated ESVD (October, 2021) that now includes over 900 studies published until 2020 (https://www.esvd.net/). Second, for this assessment we assumed a null value (0 €/ha/year) for urban areas, as the global value functions did not present any ecosystem service value for urban biomes, although it is known – and we acknowledge so – that there are values associated with urban ecosystems as they contain green areas (e.g. parks, squares, vegetable gardens, woods) and other services that urban areas themselves may provide. Finally, it is important to highlight that the observed increase in ESV over the years deserves careful consideration. A possible economic slowdown and/or population decrease in combination with the current natural capital consuming economic model for growth, could lead to jeopardizing the ecosystems, services and values due to increasing demand for and decreasing supply of ES.

Ecosystem service value changes are exponentially related with flood risk and economic growth, such that small changes in flood or income lead to large changes in ESV. Unlike previous studies (see e.g. Martinez et al., 2007; Roebeling et al. 2013; Paprotny et al., 2021), the ESV established in this study are dependent on time and local conditions, such as population and income for reference and future scenarios. As an increase in population and income is expected in the future (2100), thus generating an increase in ESV, it emphasizes the values at risk.

This study aims to create awareness about which ecosystem services and biomes present the highest associated values in each region and country along the Atlantic coastal zone as well as which of these are most at risk due to climate change, sea-level rise and socio-economic development. Hence, it provides the evidence and emphasizes the need to maintain and conserve natural ecosystems for present and future generations.

Finally, the perception of the importance of human, social and built as well as natural capital services and values are crucial in the development of coastal adaptation strategies. Coastal adaptation strategies should be based on full welfare analyses that considers human, social and built as well as natural capital services and values. This study helps as a warning, indicating regions on the Atlantic coastal zone that may suffer, more severely, with the sea level rise process, and can therefore support coastal protection planning assisting adaptation strategies.

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