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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 result 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.

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, 2003; Barbier et al., 2008; Rao et al., 2015; Neumann et al., 2015; Mc Michael et al., 2020) – and 80 % to 100 % of the total population of more than half of coastal countries live within 100 km from the coastline (Burke et al., 2001; Neumann et al., 2015; Mc Michael 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

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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 et al., 2021; Eastman, 2021).

Various papers seeking to value coastal ecosystem services and values have been published over the last decades. Martínez 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.

2. Methods and data

The methodology integrates multiple datasets and models to obtain projections of ecosystem service values at risk of flooding (see Fig. 1). This section describes the used Ecosystem service value functions (Section 2.1), the applied Uncertainty Bathtub Model (uBTM; Section 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 2.4).

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 1).

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 2.

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 Fig. 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).

In this study, we adopted the uBTM methodology by de Lima et al. (2021; see Fig. 2). The model adopts the lowest vertical error of a DEM and the sea-level rise projection with the highest estimation (Fig. 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 and 100 %; see Fig. 2c). As inputs, we use of the

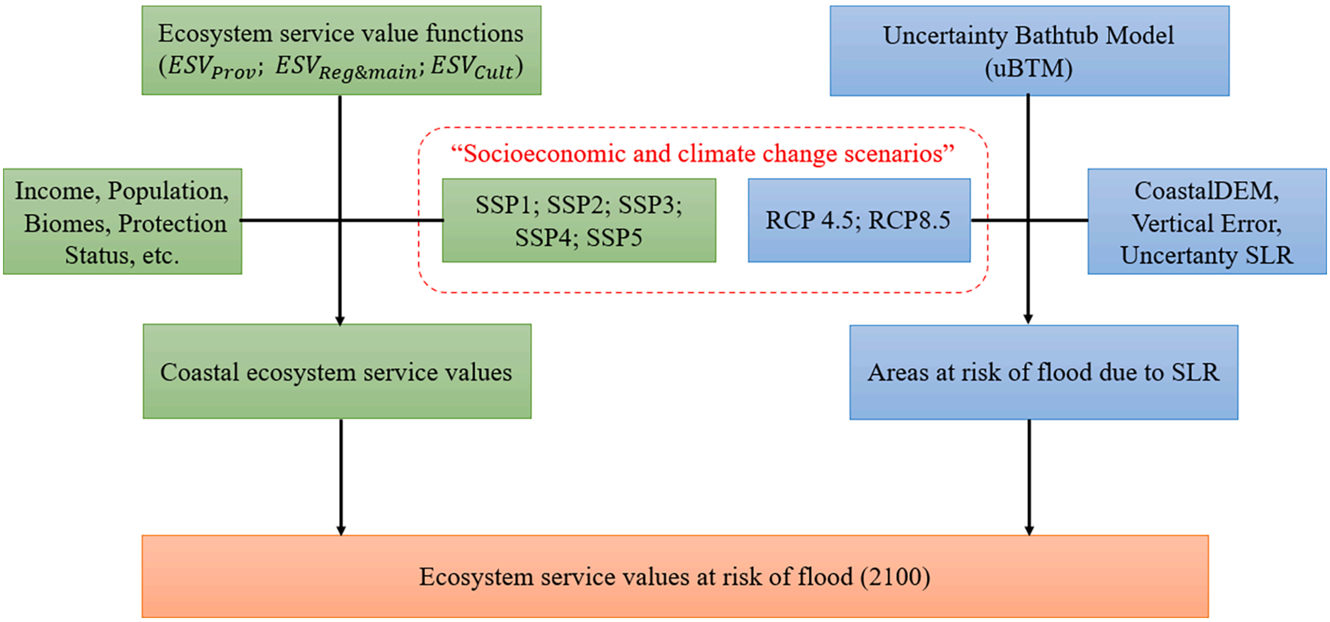

Fig. 1. Flowchart of the main elements of the methodology.

Table 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 m in situ, by percentage of land area.	
MProt	Percentage of marine protected areas, within territorial waters of a country.	
TProt	Percentage of terrestrial areas totally or partially protected, designated by national authorities.	World Bank (2021)
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 (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.	

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.

Table 2
Value function model specification for ecosystem services[1] (Source: Magalhães Filho et al., 2021).

Explanatory variables[2]	ESV_{Prov}[1] *Coef*	$ESV_{Reg\&main}$[1] *Coef*	ESV_{Cult}[1] *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_{Prov} = Provisioning ecosystem service values; $ESV_{Reg\&main}$ = Regulating & maintenance ecosystem service values; ESV_{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.

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,

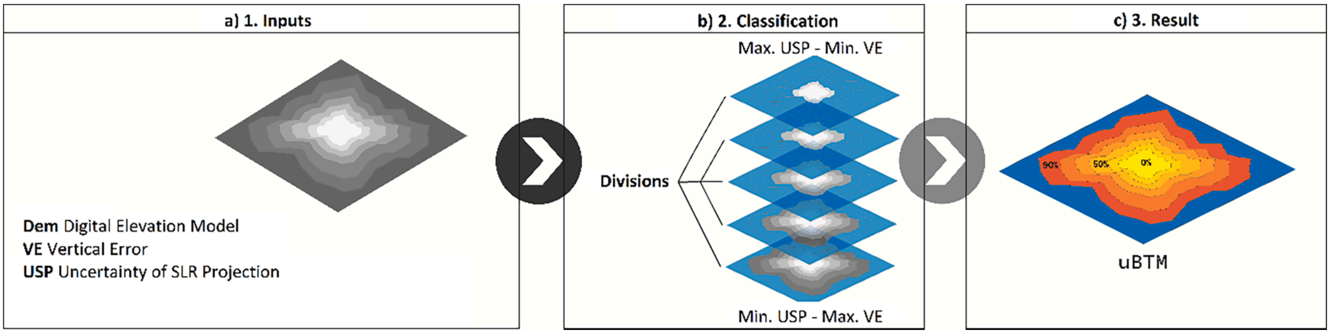

Fig. 2. The Uncertainty Bathtub Model conception (adapted from de Lima et al., 2021).

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 and 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 and 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 and 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 and 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 et al., 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 (Riahi et al., 2017) to obtain the values for the explanatory variables for the SSP scenarios (see Table 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).

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, 2020; see Fig. 3).

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 Fig. 4.

Next, we reclassify land cover data from the Climate Change Initiative - Land Cover (CCI-LC; ESA Climate Change Initiative, 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 based in Magalhães Filho et al. (2022), 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 Fig. 4).

The land cover database provides the area of each biome as well as

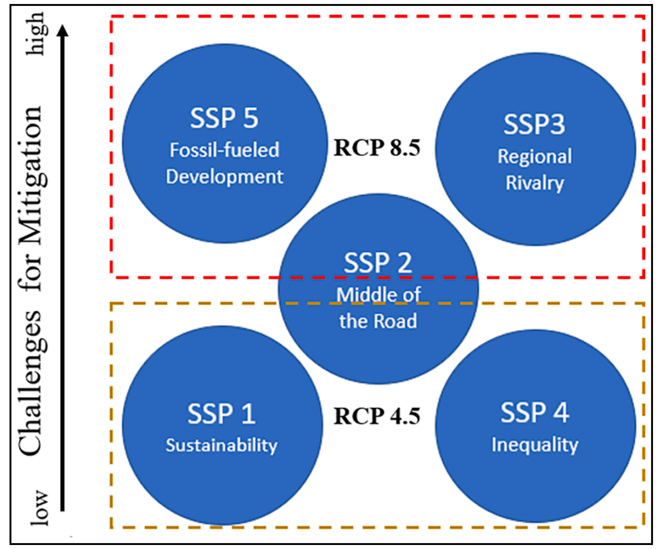

Fig. 3. Scenario combinations between RCP and SSP (adapted from Auer, 2020).

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; see Table 1), and for 2100 we adopt data from

Table 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.

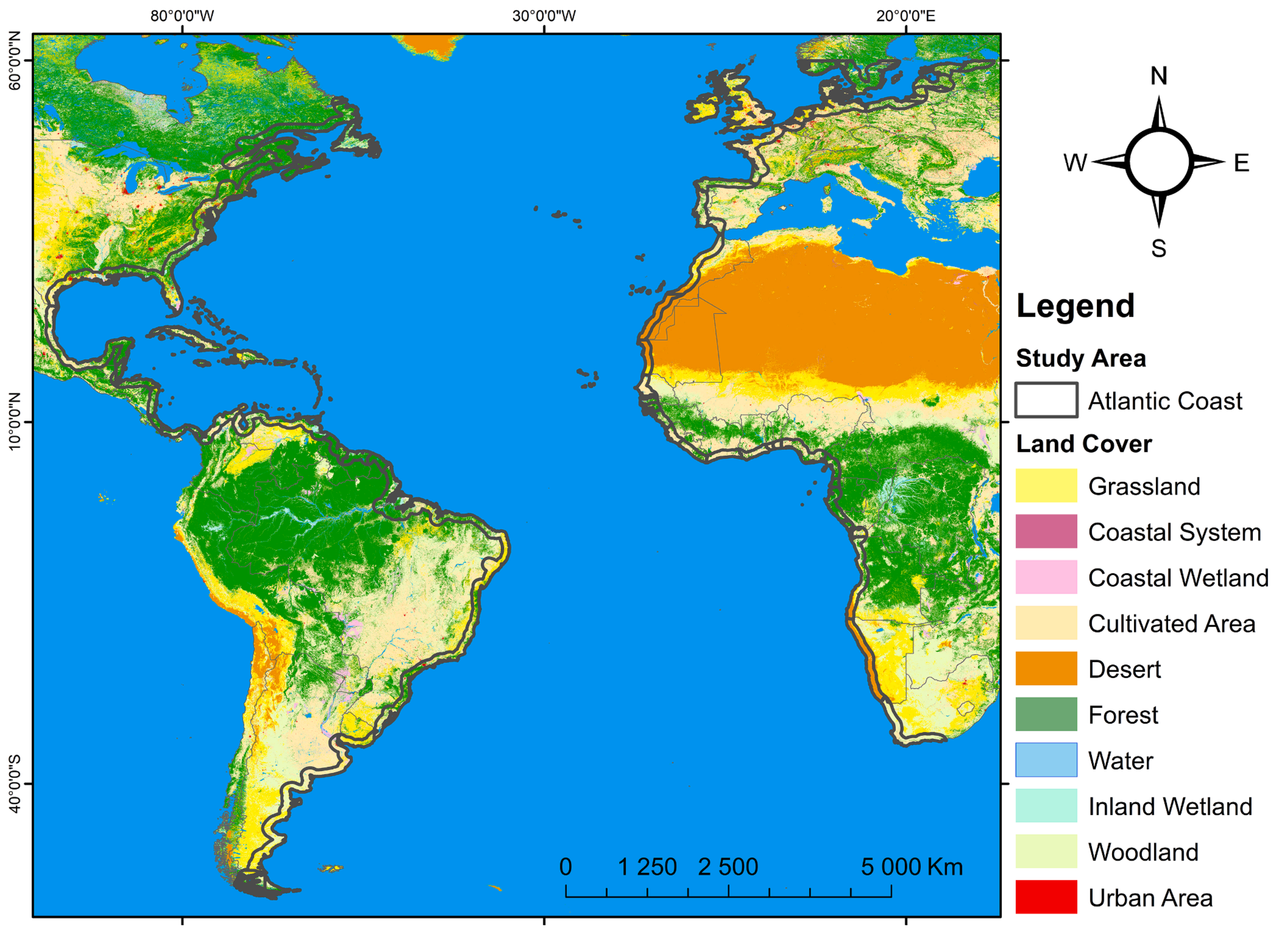

Fig. 4. Map of land cover in Atlantic Coastal Zone in 2015.

SSP 1 to 5 from International Institute for Applied Systems Analysis - IIASA (2020; see Table 3). For the Uncertainty Bathtub Model application, we use the digital elevation model from CoastalDEM (see Section 2.2) and the SLR Projections from RCP 4.5 and 8.5 (IPCC, 2013; see Section 2.3).

3. Results

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 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). If the reader wishes to consult the unit ecosystem service values for each country, please refer to Table A1 in the Supplementary Material.

Note that these ESV suffer alterations for projections towards 2100, due to changes in socioeconomic conditions (as per Table 3) – in particular income and population density.

Table 4
Average Atlantic Coast unit ecosystem service values (ESV) per biome in the 2015, reference year (€/ha/year, 2015 price levels).

Biome[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.

3.2. Risk of flood due sea-level rise

Fig. 5 shows the results of the Uncertainty Bathtub Model (uBTM), where Fig. 5a to 5c present the maps of the areas at risk of flood for RCP 4.5 by 2100 and Fig. 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 % (Fig. 5c and 5f), and between Mexico and the

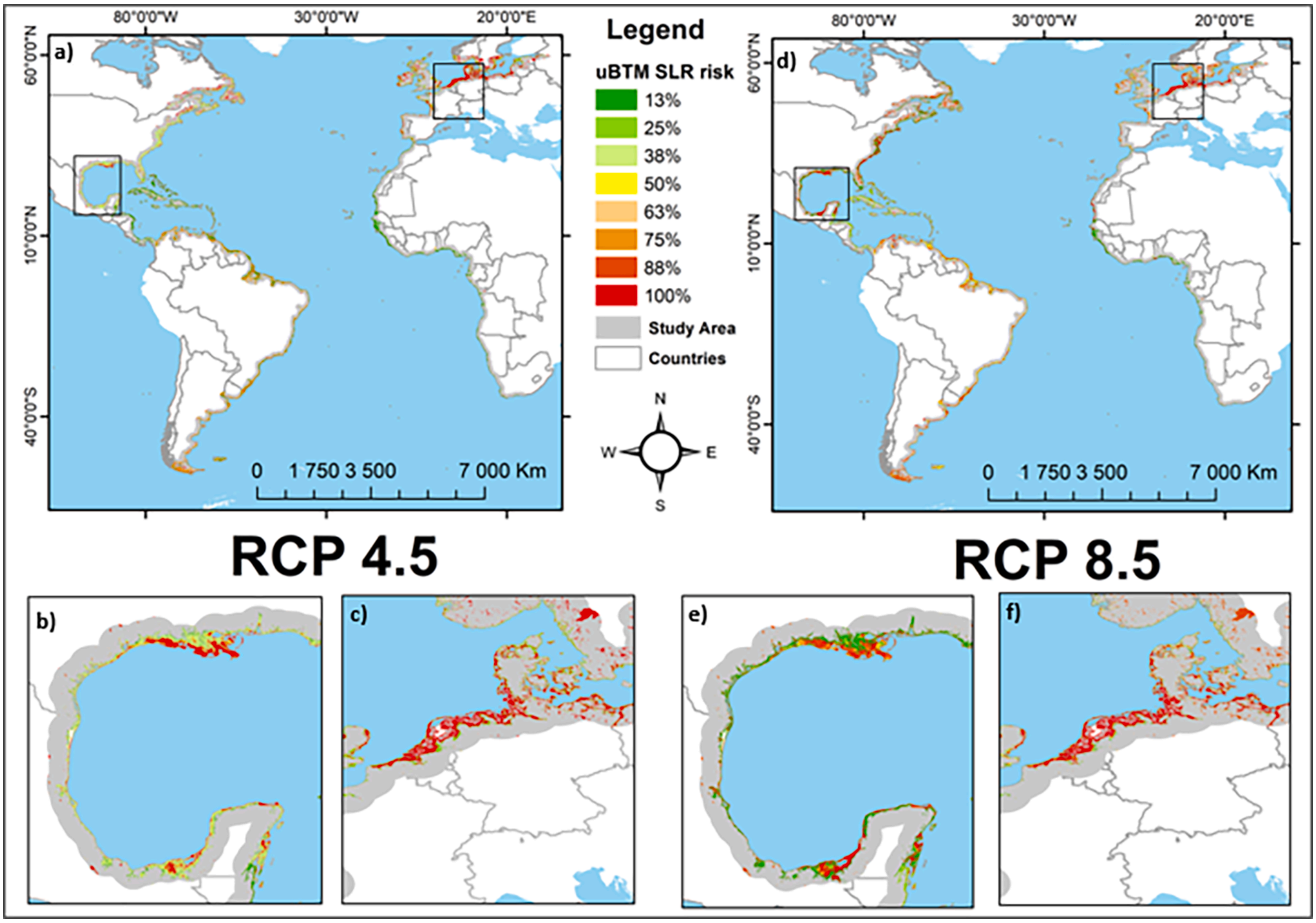

Fig. 5. Areas at risk of flood for RCP 4.5 (a) to c)) and RCP 8.5 (d) to f)) by 2100 (based on uBTM results). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

United States, with a risk of loss between 4.9 % and 6.0 % and 4.4 %-5.6 % respectively (Fig. 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 A1 in the Supplementary Material.

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

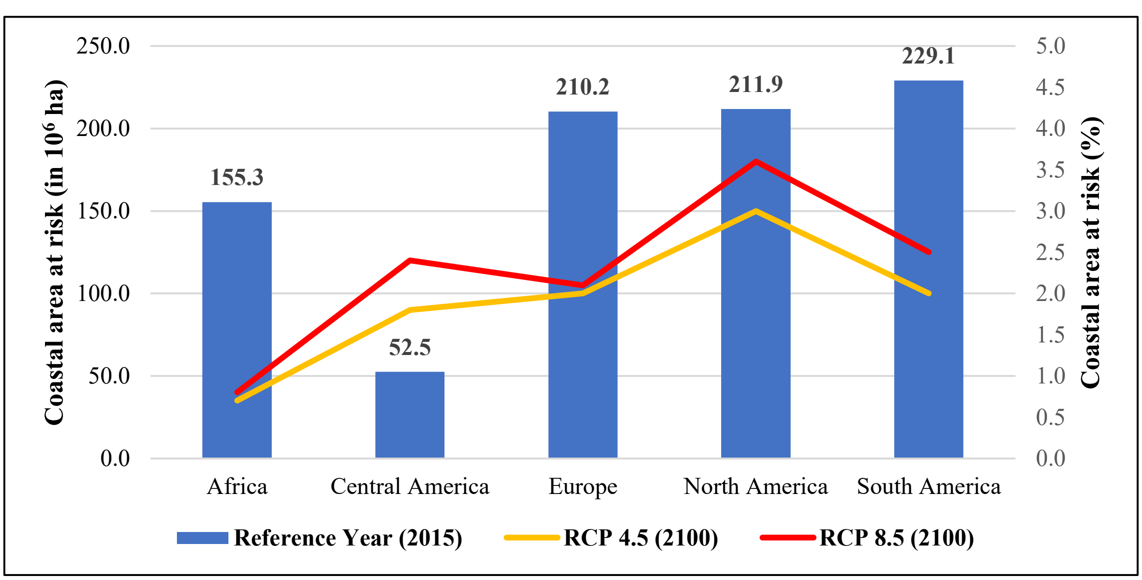

Fig. 6. Atlantic coastal zone area (in ha) and percentage (in %) at risk of flood due to sea-level rise per continent for Reference Year (blue, left axis), RCP 4.5 (orange, right axis) and RCP 8.5 (red; right axis) by 2100 (based on uBTM results).

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. Fig. 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.

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 5 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 dieback and increase in salinity due to direct tidal flushing.

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 Fig. 7) and for the ESV at risk according to the scenarios (for 2100; see Fig. 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.

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 Fig. 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. Fig. 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. To verify the value of each scenario by continent, please refer to Table A2 in the Supplementary Material.

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. Fig. 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, Fig. 10 shows those for RCP 8.5, which presents the percentage losses for taking into account the SSP2, SSP3 or SSP5.

For RCP 4.5, by 2100, the countries facing highest relative 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 %).

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

Table 5

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 RY (2015)	Area at risk due to SLR			
		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.

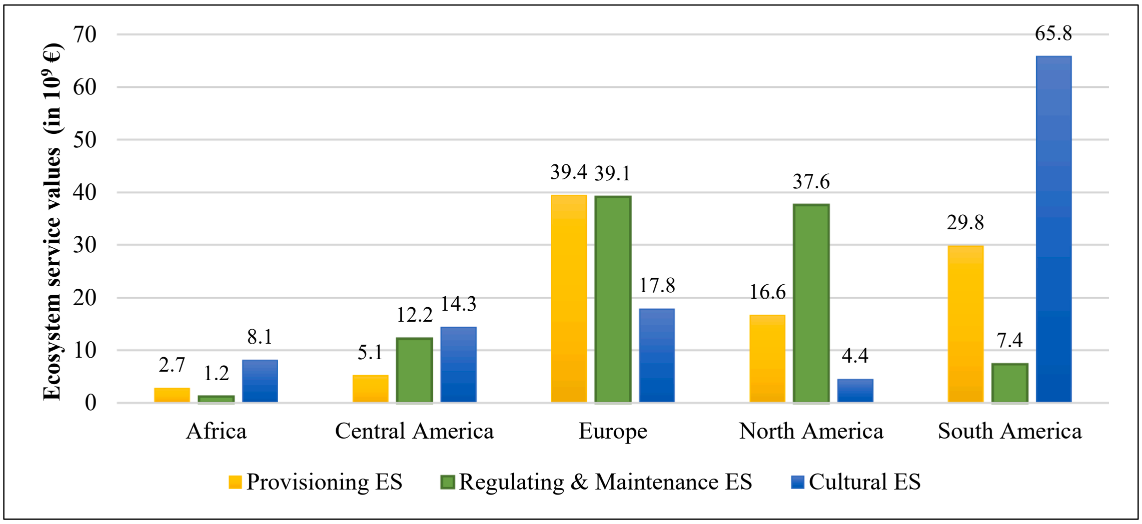

Fig. 7. Provisioning, Regulating & maintenance and Cultural ecosystem service values (ESV) for the Atlantic Coastal Zone per continent in the 2015 reference year (in 10^9 €/year; 2015 price levels).

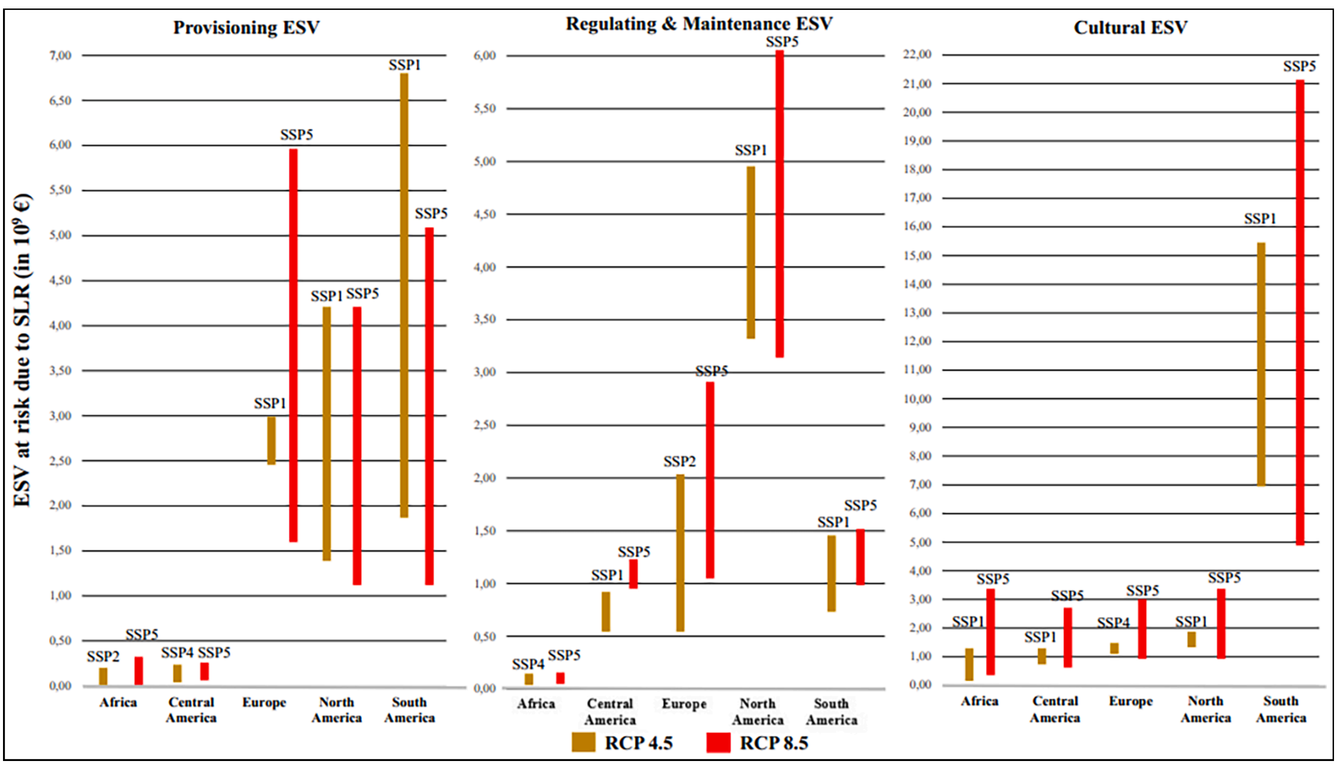

Fig. 8. Ecosystem service values (ESV) at risk of flood due to sea-level rise by RCP and SSP scenario for each continent by 2100 (in 10^9 €/year; 2015 price levels).

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.

4. Discussion

4.1. Comparison with other studies

Our results can be compared with those from similar previous studies, performed for world (Martínez et al., 2007) and European (Roebeling et al., 2013; Paprotny et al., 2021) coastal zones (see Table 6). 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 Martínez et al. (2007), as their coastal zone is delimited by a 100 km buffer (thus including a larger share of ecosystem services with

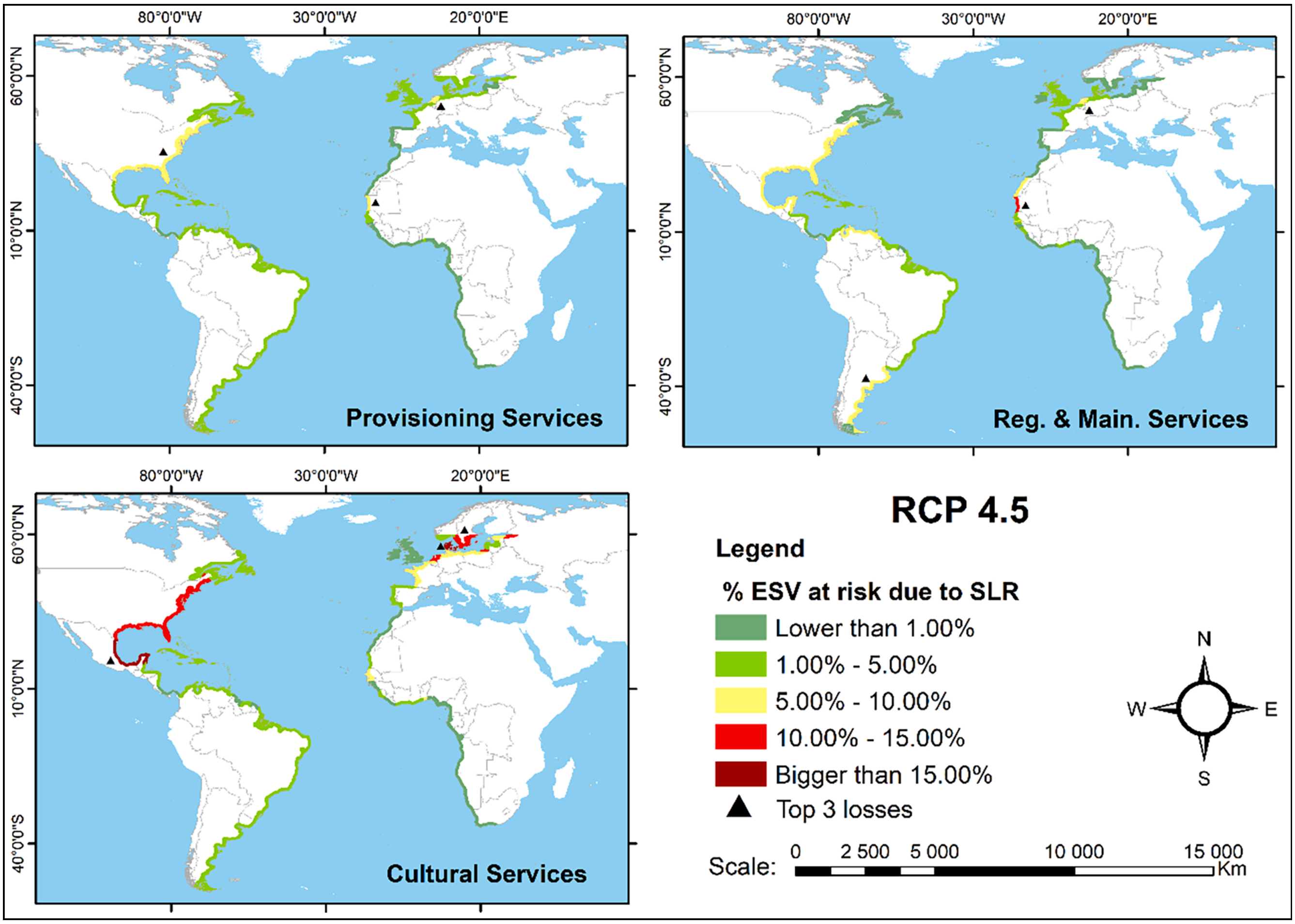

Fig. 9. Potential ecosystem service values (ESV) at risk due to sea-level rise for RCP 4.5 by 2100.

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.

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; Paprotny et al., 2021; see Table 7). 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 & Swart, 2000). The SRES scenarios were superseded by the RCP scenarios in the IPCC fifth assessment report in 2014 (Riahi et al., 2017). Paprotny 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).

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 and 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 Paprotny et al. (2021). The estimated areas at risk until 2050 by Roebeling et al. (2013) are above (considering the projected year) those from Paprotny 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. (2013) and somewhat below those from Paprotny et al. (2021), given the larger estimated area at risk and/or used unit ecosystem service values.

5. Limitations

The land cover used in this study was the CCI-LC, a worldwide database with 300 m 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

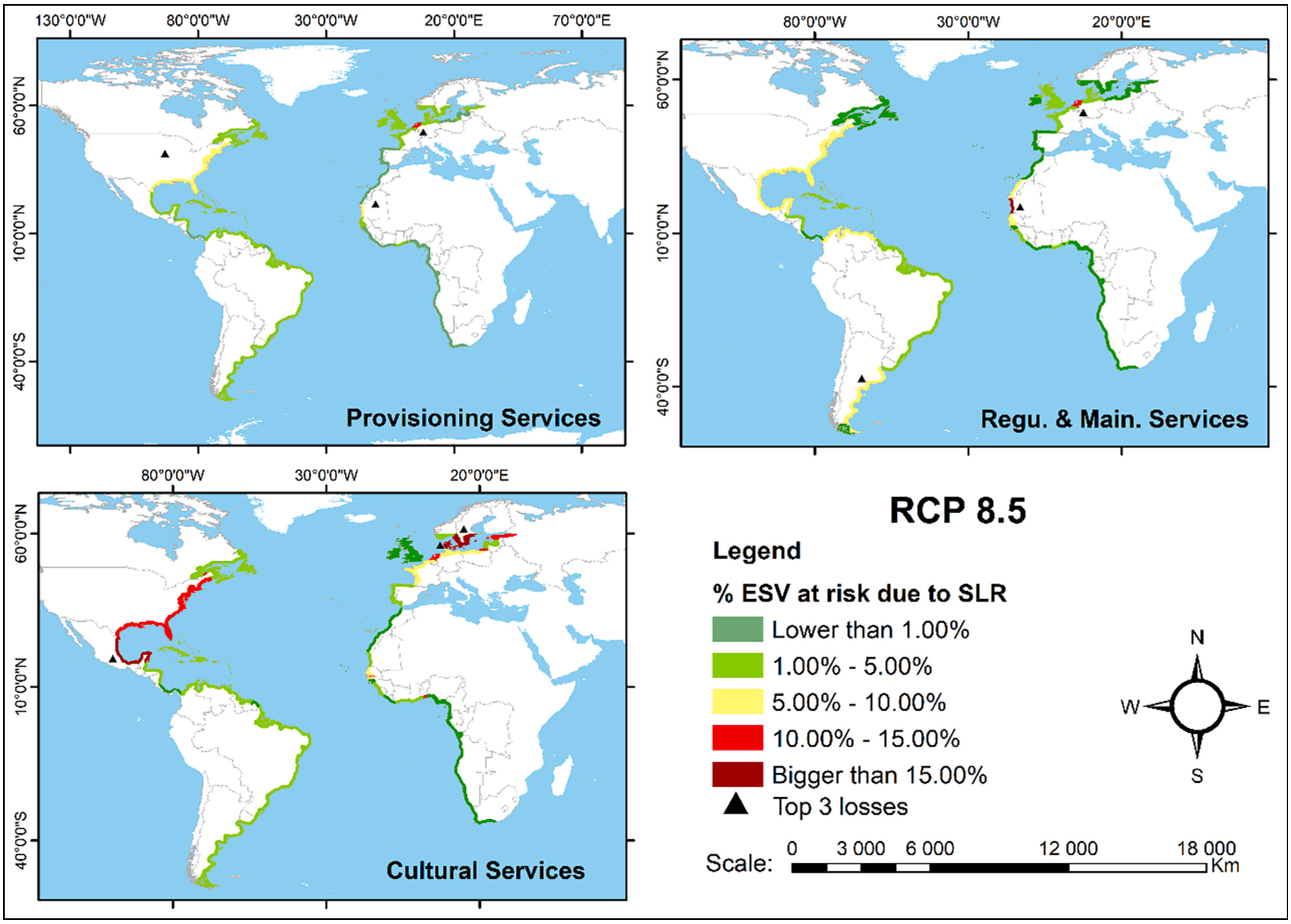

Fig. 10. Potential ecosystem service values losses due to sea-level rise RCP 8.5 by 2100.

Table 6
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)
Martínez 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
Paprotny et al. (2021)	European coast	2018	58.0	485.7	8,378.5
This study	Atlantic coast	2015	859.0	301.5	351.0

Table 7
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 %
Paprotny 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 %

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 and 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).

6. 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. Martínez 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.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2022.101492.

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