Climate Risk Management 39 (2023) 100470

Contents lists available at ScienceDirect

Climate Risk Management

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

Land loss implications of sea level rise along the coastline of Colombia under different climate change scenarios

Hannes Nevermann [a,*], Jorge Nicolas Becerra Gomez [a], Peter Fröhle [b], Nima Shokri [a,*]

[a] Institute of Geo-Hydroinformatics, Hamburg University of Technology, Am Schwarzenberg-Campus 3 (E), 21073 Hamburg, Germany
[b] Institute of River and Coastal Engineering, Hamburg University of Technology, Denickestraße 22, 21073 Hamburg, Germany

A B S T R A C T

The sea level has risen notably in recent decades compared to the most recent millennia. This poses serious threats to infrastructure, local jobs, environment and human population over the next century, especially in coastal zones. In this paper, the most up-to-date understanding of the climate system and climate change was used to investigate impacts of sea level rise on potential land loss along the Caribbean and Pacific coastlines of Colombia. Sea level rise projections published in August 2021 by the Intergovernmental Panel on Climate Change in the Sixth Assessment Report were used to identify the area at risk of land loss. Moreover, the potential socio-economic implications of these changes were discussed in regions affected by the projected sea level rises. We examined five Shared Socioeconomic Pathways for the 21st century (SSP1-1.9, SSP1-2.6, SSP2-4.5. SSP3-7.0, SSP5-8.5). Our results suggest a sea level rise of 1.04 m in the worst-case scenario (SSP5-8.5) which would threaten an area of 2840.64 km^2. The land use in the affected zones was determined. The area at risk will impact 12 departments or 86 municipalities with different social, environmental, economic, and cultural conditions along the coastline of Colombia, that need to be considered when devising and implementing mitigation policies.

1. Introduction

Sea level rise (SLR) is one of the consequences of climate change and may pose serious environmental and socio-economic challenges, especially in coastal environments. SLR exacerbates the impacts of extreme sea level events as well as coastal hazards, and has several detrimental effects on marine ecosystems and services (Moftakhari et al., 2017; Fagherazzi et al., 2020; Masson-Delmotte et al., 2021; Martyr-Koller et al., 2021; van den Hurk et al., 2022). The United Nations states that about 40 % of the world's population lives in coastal regions, i.e. within 100 km of the coastline (Barbier, 2015; Montgomery, 2007). The land area that is less than 10 m above sea level is just 2 % of the world's total land area, yet it is home to 10 % of the world's population and 13 % of the world's urban population (McGranahan et al., 2007). SLR, extreme sea level events, and land subsidence have the potential to significantly affect landscapes, land use, infrastructure, morphology and ecosystem services, therefore coastal areas are among the most vulnerable regions in the world (Nicholls & Cazenave, 2010; Davtalab et al., 2020). Estimations from the Intergovernmental Panel on Climate Change (IPCC) suggest a future increase in Global Mean Sea Level (GMSL) rise. Such a trend can already be observed when, for example, comparing the rate of change of 3.7 [3.2 to 4.2] mm/yr between 2006 and 2018 with the rate of 1.9 [0.8 and 2.9] mm/yr between 1971 and 2006 (Masson-Delmotte et al., 2021). In order to effectively develop ways to adapt, regional and local drivers must first be determined. Authorities and stakeholders require information regarding how sea level rise will impact specifically their local

* Corresponding authors at: Institute of Geo-Hydroinformatics, Hamburg University of Technology, Am Schwarzenberg-Campus 3 (E), 21073 Hamburg, Germany.

E-mail addresses: hannes.nevermann@tuhh.de (H. Nevermann), nima.shokri@tuhh.de (N. Shokri).

https://doi.org/10.1016/j.crm.2022.100470
Received 26 April 2022; Received in revised form 15 December 2022; Accepted 16 December 2022
Available online 17 December 2022

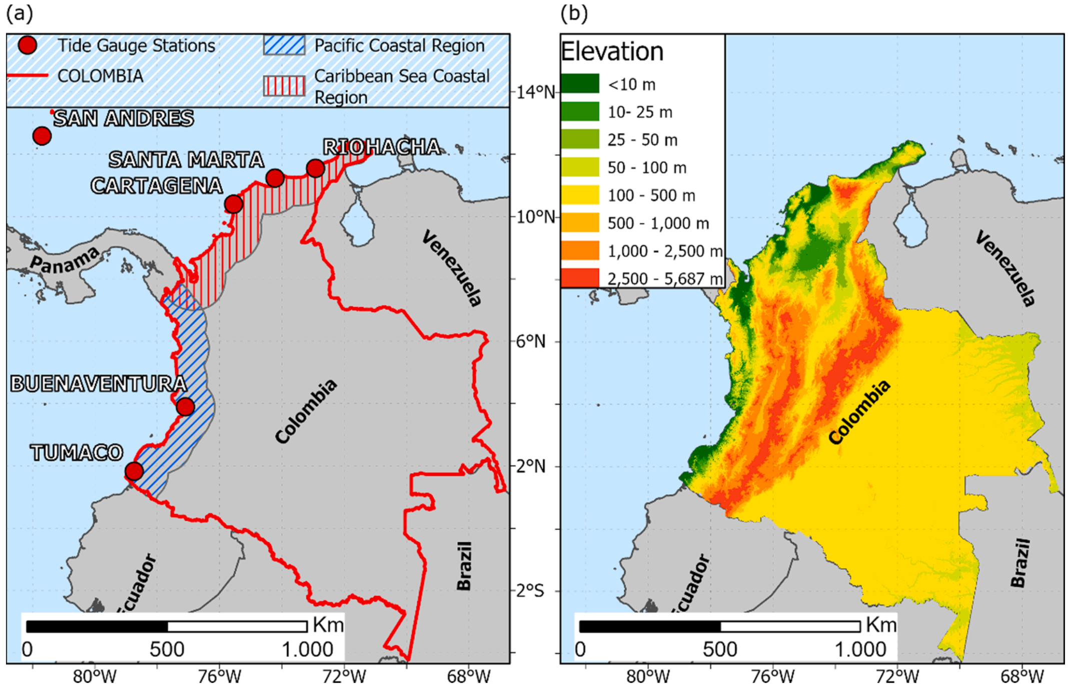

Fig. 1. (a) Map of Colombia showing tide gauge stations as well as the 100 km coastal zone for the Pacific and the Caribbean coasts (hatched zones). (b) Elevation of Colombia. The legend indicates the elevation above the sea level.

area in order to implement future development plans.

This study aims to analyze impacts on the coastline of Colombia. Colombia extends from north to south between 12°N and 4°S and from east to west between 67°W and 79°W (Fig. 1a) with a total area of nearly 1.14 million km^2 and it is home to nearly 51.3 million people (The World Bank, 2022). It is composed of 32 departments (subnational divisions) plus the capital district of Bogota, and it shares borders in the North with Panama, in the East with Venezuela and Brazil and in the South with Ecuador and Peru. The climate is predominantly tropical along the coast and in the eastern plains, whereas the highlands are characterized by a cooler climate. The overall coastline of Colombia is more than 3000 km in length, with over 1600 km on the Caribbean Sea and about 1400 km along the Pacific Ocean (Fig. 1a).

Rising sea levels and an increase in the occurrence of extreme events are recognized as key climate concerns by policymakers and the global public (Oppenheimer and Alley, 2016). Sea level rise threatens coastal areas through a combination of hazards and impacts, including intensification of episodic, temporary flooding, as well as permanent inundation of land, inundation of groundwater, and salinization of ground and surface waters (Magnan et al., 2022). Additionally, marine and terrestrial coastal ecosystems will undergo significant changes by the end of this century, which include the loss of biodiversity and ecosystem functions (Albright et al., 2018; Blankespoor et al., 2014; Borchert et al., 2018; Coldren et al., 2019; Perry et al., 2018).

Similar to other regions around the globe, SLR in Colombia is expected to cause flooding and coastal erosion (Restrepo-Ángel et al., 2021). This study analyses three different aspects of SLR consequences along the Colombian coasts. Firstly, by using different IPCC scenarios, potential land loss due to SLR will be determined. Secondly, the current land use of these threatened areas will be assessed. Finally, a socio-economic discussion will be presented to delineate the potential impact of SLR with the associated land loss on the local population.

2. Methods

2.1. Elevation information from Colombia

Digital Elevation Model (DEM) data is needed to assess land elevation compared to SLR and thus determine potential land loss as a result of the projected SLR. The data used in this study is a high accuracy Multi-Error-Removed Improved-Terrain DEM (MERIT DEM) with a resolution of 3 arc seconds (~90 m at the equator), that was created by removing the key error components from existing DEMs (NASA SRTM3 DEM, JAXA AW3D DEM, Viewfinder Panoramas DEM) (Yamazaki et al., 2017). Yamazaki et al. (2017) used a multi-step method to improve the accuracy of the global DEM. Firstly, strip noise was removed, then the absolute bias and the tree height bias were identified and removed and as a last step the speckle noise was removed by using adaptive smoothing filters. Each dataset represents 5° (latitude) by 5° (longitude) tiles. For the analysis, we merged several tiles in a mosaic dataset using the same geographic coordinate system (WGS 1984). Fig. 1b illustrates the results of DEM analysis.

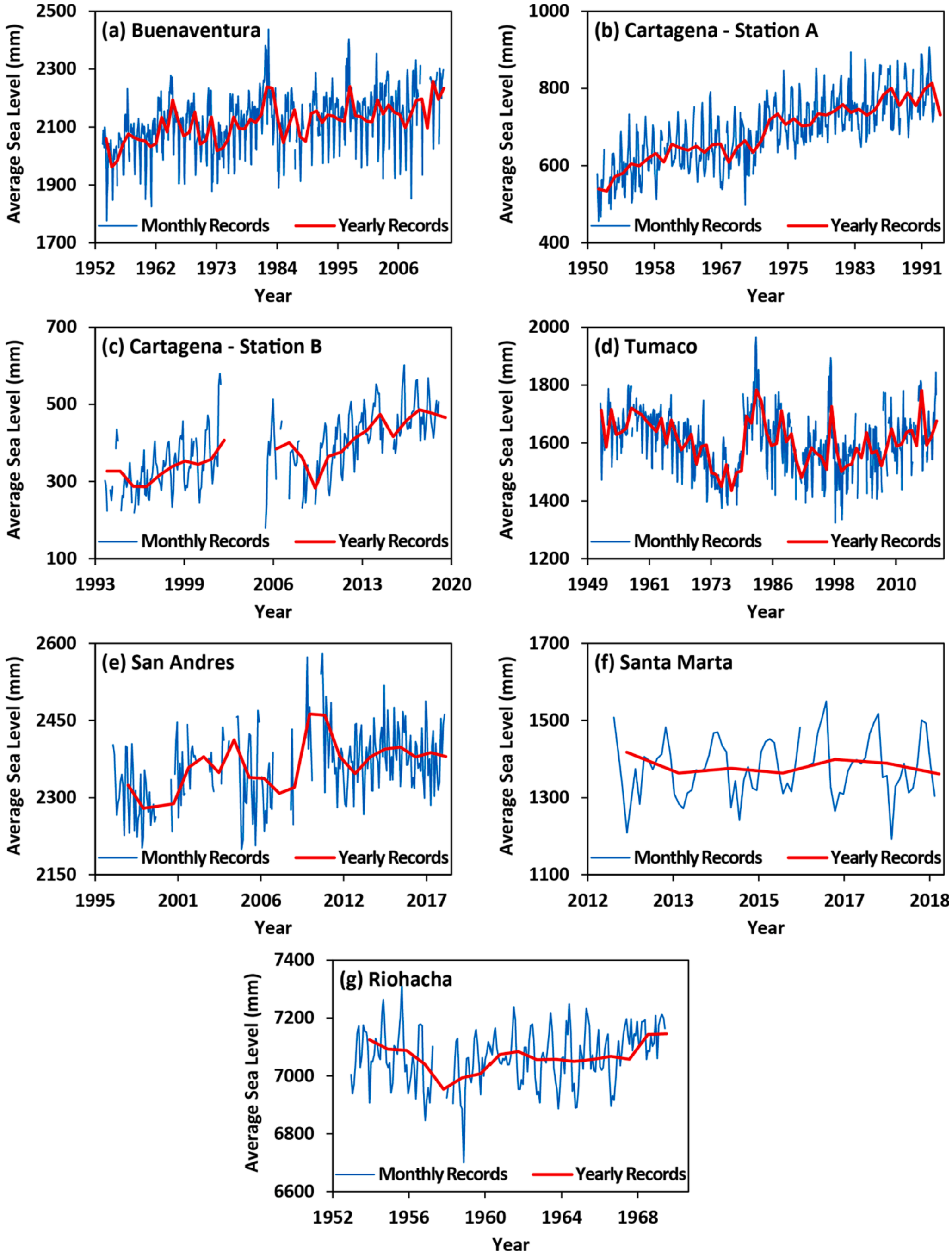

Fig. 2. Sea level rise values based on the monthly and annually averaged data measured by the tide gauge stations shown in Fig. 1a.

For the predicted future scenarios, the inundated area is calculated according to the elevation value from the DEM. For each scenario, the area is determined by connected pixels that have a value less than or equal to the sea level rise.

2.2. Tide gauge information from Colombia

Two organizations, the Permanent Service for Mean Sea Level (PSMSL), which offers a global data bank for long-term sea level change information including, the Global Sea Level Observing System (GLOSS), and the University of Hawaii Sea Level Center (UHSLA), collect tide gauge data on the coasts of Colombia. The two tide gauge stations located on the Pacific coast are Buenaventura and Tumaco and the four stations located on the Caribbean coast are San Andres, Cartagena, Santa Marta and Riohacha (Fig. 1a). Each

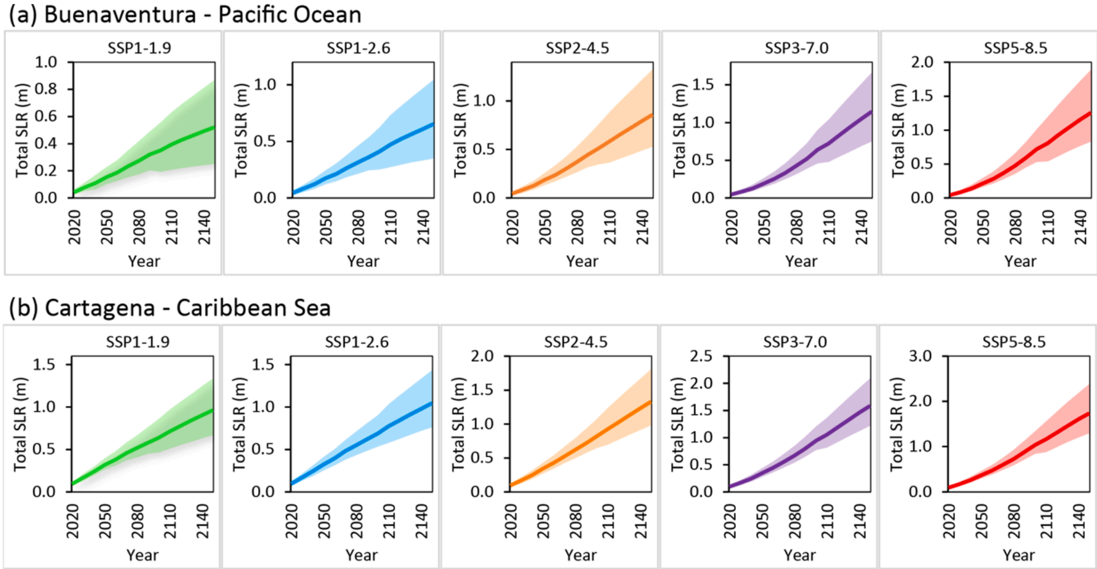

Fig. 3. Buenaventura (a) and Cartagena (b) total sea level rise. Shaded zones show the 17th-83rd percentile ranges. Projections are relative to a 1995–2014 baseline.

tide gauge station is part of a network of stations belonging either to the PSMSL - GLOSS or to the UHSLC. The quality assessment of the sea level data can be found in their metadata. There are two different types of datasets available for each station. One is fast delivery data, which is released within 1–2 months of data collection and receives only basic quality control which focuses on large sea level shifts and obvious outliers. The other data type is "science-ready" data which follows an in-depth quality control process that is time-consuming and results in research quality data. However, this process may take up to 2 years until data release. In our analysis, data in research quality was used from PSMSL – GLOSS for the tide gauge stations Buenaventura, Cartagena and Tumaco. Fast delivery data from the UHSLC was used for the stations Buenaventura, Cartagena, Tumaco, San Andres and Santa Marta. The recorded data from these stations are presented in Fig. 2.Note that the tide gauge recordings start at different years and there was a recording gap in Cartagena – Station B.

2.3. Projected climate changes and sea level rises

The IPCC has developed sea level scenarios by establishing emissions-dependent probabilistic projections and discrete scenarios-based methods (Pachauri et al., 2014). Each emissions scenario is represented by a Representative Concentration Pathway which describes different climate futures, depending on the volume of greenhouse gases emitted in the coming years. Moreover, the climate change research community has developed different scenarios incorporating future changes in climate and society to explore different alternatives for mitigation and adaptation (O'Neill et al., 2017). These scenarios, known as Shared Socioeconomic Pathways (SSP), include key aspects of society such as demographics, human development, economy and lifestyle, policies and institutions, technology and environment and natural resources and are assessed to identify challenges that are due to mitigation and adaptation. In the most recent report published by the IPCC (Masson-Delmotte et al., 2021), Integrated Assessment Models (IAM) are being used to create different scenarios of energy use, air pollution, land use, and greenhouse gas emission. The implementation of mitigation policies or lack of them could develop numerous emission scenarios for each SSP (Riahi et al., 2017). The IPCC's Sixth Assessment Report (Masson-Delmotte et al., 2021) relates an SSP with a radiative force level at the end of the 21st century depending on the mitigation and adaptation and the emission future within the IAM modeling framework. For example, the SSP1-1.9 scenario represents the SSP1-Sustainability together with a policies and emission framework that would reach a radiative forcing of 1.9 W/m^2 value by 2100. The core SSP scenarios used in the IPCC report are SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 (Masson-Delmotte et al., 2021) therefore, we decided on using these scenarios in this study.

The IPCC analyses and assesses the scientific-experimental information and produces unified projections on future sea levels across the world under a variety of potential future scenarios. The NASA Sea Level Projection Tool (Fox-Kemper et al., 2021; Garner et al.,2021) is created to visualize and download the sea level projection data from the IPCC 6th assessment report. Sea-level change for each SSP scenario results in medium confidence (50th percentile) and two low confidence (17th and 83rd percentile range) scenarios adding several other SLR drivers such as ice sheet and thermal expansion (among other parameters). We used the NASA Sea Level Projection Tool to project SLR from 2020 to 2150 under different future climate scenarios for the tide gauge station Cartagena on the Caribbean coast and the station Buenaventura on the Pacific coast. The projected values are presented in Fig. 3 (note that the corresponding tabulated values are reported in Table SM.1).

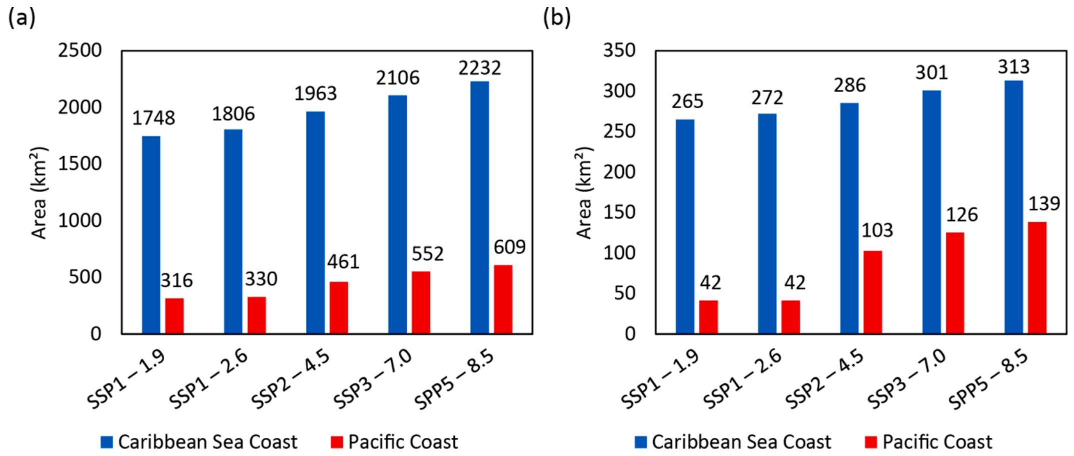

Fig. 4. Potential land loss due to the projected sea level rise for the Caribbean Sea coast and the Pacific coast within the (a) 100 km and (b) 1 km of coastlines.

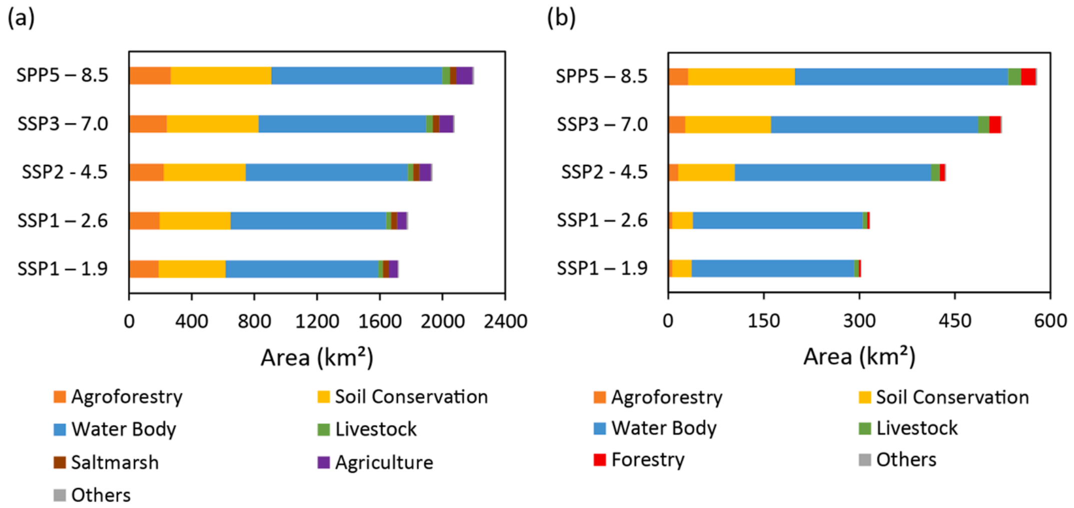

Fig. 5. Land use of the area in potential risk of land loss due to the projected sea level rise on the (a) Caribbean and (b) Pacific coastlines.

3. Results

Over the last few years, a clear SLR is seen in the Caribbean Sea, whereas a slower SLR is observed in the Pacific Ocean.

3.1. Potential land loss due to SLR according to the IPCC scenarios

Based on the previously projected SSP scenarios, the potential land loss on the Pacific and Caribbean Sea coast due to SLR was calculated. Only the area located within the 100 km coastal region (Fig. 1a) was used for the calculation with the data presented in Fig. 4a. Even though the Caribbean coast of Colombia (with around 1600 km length) is only 1.15 times as long as the Pacific coastline (less than 1400 km length), the area at risk is over 5.5 times larger on the Caribbean coast under SSP1-1.9. Under SSP1-2.6. SSP2-4.5, SSP3-7.0 and SSP5-8.5 the area at risk is still 5.5, 4.2, 3.8 and 3.7 times larger on the Caribbean coast. The total area at risk within the 100 km zone (on both Pacific and Caribbean Sea coast) is around 2064 km^2 under SSP1-1.9, 2136 km^2 under SSP1-2.6, 2424 km^2 under SSP2-4.5, 2658 km^2 under SSP3-7.0 and 2841 km^2 under the SSP5-8.5 Scenario.

Our results indicate that the Caribbean Sea coastline will experience a higher SLR than the Pacific Ocean coastline. This could be the result of natural factors such as tectonic activity and sediment compaction (Restrepo-Ángel et al., 2021). As reported in supplementary material, Table SM.1, the Caribbean Sea will undergo a sea level rise between 0.64 m (SSP1-1.9) and 1.04 m (SPP5-8.5) whereas the Pacific Ocean will experience a lesser impact with a sea level rise between 0.35 m (SSP1-1.9) and 0.72 m (SSP5-8.5). An area of 1748 km^2 and 2232 km^2 along the Caribbean Sea coast is at risk of permanent loss under SSP1-1.9 and SSP5-8.5, respectively (Fig. 4a) while these numbers are 316 km^2 and 609 km^2 for the Pacific coast (Fig. 4a). If the SLR would exceed the values of the future projections used

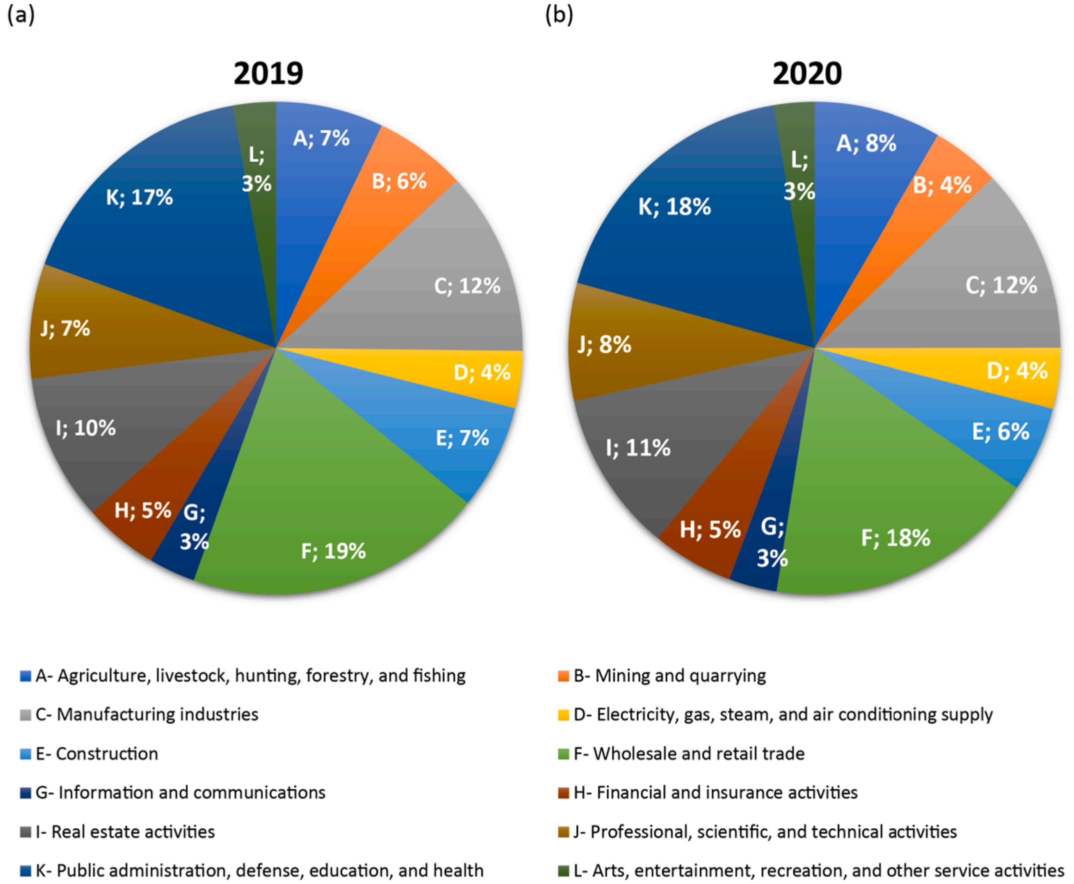

Fig. 6. Gross Domestic Product by branch of economic activity for the year 2019 (a) and 2020 (b) (DANE, 2020b).

Table 1
Department GDP percentage by branch of economy activity (%) presented in Fig. 6 (DANE, 2020b).

Department	Industry code											
	A	B	C	D	E	F	G	H	I	J	K	L
Antioquia	12.97	12.25	19.07	19.50	16.10	14.30	14.70	15.99	14.64	19.86	11.27	14.15
Córdoba	2.83	1.83	1.78	2.05	1.94	1.41	1.77	0.85	0.66	1.76	3.06	1.23
Chocó	1.15	2.26	0.03	0.12	0.33	0.29	0.15	0.17	0.09	0.01	0.98	0.15
Sucre	1.10	0.12	0.52	0.54	1.56	0.79	0.66	0.45	0.51	0.27	1.76	0.94
Atlántico	0.64	0.25	6.15	9.66	4.16	5.40	4.00	4.21	3.72	4.67	4.55	4.44
Bolívar	2.44	2.17	4.76	3.39	5.76	2.91	2.37	1.83	2.59	3.39	4.14	2.09
Magdalena	3.26	0.08	0.48	0.70	1.53	1.53	1.16	0.78	0.92	0.69	2.48	1.14
La Guajira	0.69	3.61	0.06	1.58	1.11	0.71	0.35	0.36	0.49	0.04	1.47	0.66
Cauca	3.37	0.46	2.67	1.49	2.67	1.15	0.75	0.71	0.93	1.93	2.44	0.99
Valle del Cauca	9.31	0.31	14.29	9.78	6.62	10.01	8.79	8.29	13.26	12.95	8.38	8.74
Nariño	3.59	0.33	0.35	0.62	2.38	1.74	0.86	0.99	1.35	0.74	2.77	1.55
San Andrés, Providencia y Santa Catalina (Archipiélago)	0.00	0.00	0.00	0.10	0.10	0.38	0.07	0.10	0.08	0.08	0.16	0.03

in this paper, the calculated numbers reported here would be modified accordingly. Considering that the area within 1 km of the coastline is most affected by changes in mean sea level, this area should be given special consideration by policy makers to adapt to sea level rise and mitigate some impacts. Therefore, we have performed a similar analysis to calculate the area under the risk of permanent land loss due to SLR within 1 km of the coastline of Pacific Ocean and Caribbean Sea with the results presented in Fig. 4b (see supplementary materials, Table SM. 2 and Table SM. 3, for the values used to plot Fig. 4).

Fig. 5a and 5b show the land use of the area that is in potential risk of land loss due to the projected sea level rises (the numerical values used to plot Fig. 5 are presented in the supplementary materials, Table SM. 4). On both coasts, the Caribbean and the Pacific, the land type classified as “water bodies” will be affected most by the SLR under any scenario. The second most affected land type is the

Table 2
Population (2018) in the municipalities that are at potential risk of land loss due to SLR (DANE, 2020a) and GDP per capita by each department that lies within area that is at risks (DANE, 2020b).

Department	Inhabitants	Municipalities	GDP per capita (USD)
Antioquia	371,321	8	5,898
Atlántico	2,001,531	13	4,343
Bolívar	1,081,757	8	4,163
Cauca	60,809	3	3,218
Chocó	210,323	13	2,186
Córdoba	358,124	10	2,614
La Guajira	654,452	7	2,205
Magdalena	822,223	11	2,538
Nariño	355,250	8	2,561
Sucre	109,589	4	2,341
Valle Del Cauca	258,445	1	5,816

land that is dedicated for soil conservation. As is also visible in Fig. 4, the land along the Caribbean coastline is expected to experience greater impacts.

3.2. Socio-economic considerations and impacts

Colombia is an emerging economy and an economic power in the South American continent. According to the International Monetary Fund (IMF), Colombia's nominal GDP is the fifth highest in Latin America after Brazil, Mexico, Chile, and Argentina, and ranks 45th in the world. The largest industry sectors in the country are public administration, defense, education and health, wholesale and retail trade and manufacturing industries (Fig. 6: Gross Domestic Product by branch of economic activity for the year 2019 (a) and 2020 (b) (DANE, 2020b). – the numerical values used to plot Fig. 6 are presented in the supplementary material, Table SM. 5).

Our results show that under SSP5-8.5 climate scenario, 12 departments and a total of 86 municipalities are directly affected by the projected SLR via its effects on potential land loss. Table 1 shows those departments and their percentage of the total economic activity of that branch. The departments Antioquia and Valle del Cauca have a great impact on the national GDP, covering a substantial ratio in most of the economic activities.

The population that is affected by the potential land loss due to SLR could vary depending on the country's development and future adaptation policies. Nevertheless, it is possible to estimate the population that currently lives in the potentially endangered area (Table 2). In addition to the affected population, it is crucial to evaluate the economic conditions in which the inhabitants live. The first factor to be evaluated is the GDP per capita. DANE reports the GDP per capita by department, which shows an estimate of the purchasing power per population (Table 2).

4. Discussion

Along the coastline of the Caribbean Sea are many important cities such as Cartagena, Barranquilla, Santa Marta, San Andres and Riohacha, which according to Banco de la Republica de Colombia are the cities that attract a large number of tourists and generate significant employment. Resources that are extracted in this coastal zone, among others, are coal, natural gas, and salts. The region's main crops are cotton, rice, coffee, cacao, cassava, African oil palm, bananas and other fruits. Cattle ranching also plays an important role, especially for dairy products, meat and also the leather industry. The economy of the Pacific region is based on industrial deep-sea fishing and mariculture; in addition, the extraction of forests for the national and international market plays a major role, as well as industrial gold and platinum mining. Livestock is also kept and the agriculture is mainly African oil palm, banana and plantain crops.

In order to determine the impact of sea level rise on the environment and the inhabitants, it is crucial to know the land use of the area that is at risk of inundation. The major land use types on both coasts, that are at risk, are water bodies and soil conservation (Fig. 5). One of the consequences of the SLR is wetland salinization. This salinization modifies the essential physicochemical nature of the soil–water environment, raising ionic concentrations and modifying chemical balances and mineral solubility (Herbert et al., 2015). Wetland ecosystem services are among the most valuable on the planet (Mitsch et al., 2015). The services include water stabilization, flood and drought mitigation, cleaning of polluted water, shoreline protection and recharging of groundwater aquifers. Wetlands also provide a unique habitat for a large variety of flora and fauna and they act as a carbon sink and can stabilize the climate. Therefore, the environmental loss due to sea level rise will have a significant impact on the natural processes of the region. Another consequence of sea level rise is soil salinization, which adversely influences vegetation, food security and environmental health (Shokri-Kuehni et al., 2020; Hassani et al., 2021). In particular, places where groundwater with high levels of salt concentration are being used for irrigation. This poses a threat to the agriculture and food production Funakawa & Kosaki, 2007). Due to the fact that land that is used for agriculture will be affected by the sea level rise under each of the SSP scenarios, and considering that agriculture, livestock, hunting, forestry and fishing represent almost 10 % of the national GDP, sea level rise poses a serious threat to food security and socio-economic activities. The different climate zones, as well as terrains, provide Colombia with a large variety of fauna and flora species making Colombia one of the world's top 5 producers of coffee, avocado, and palm oil, and one of the world's top 10 producers of sugar cane, banana, pineapple and cocoa (Food and Agriculture Organization, 2021). Furthermore, residential zones will also be

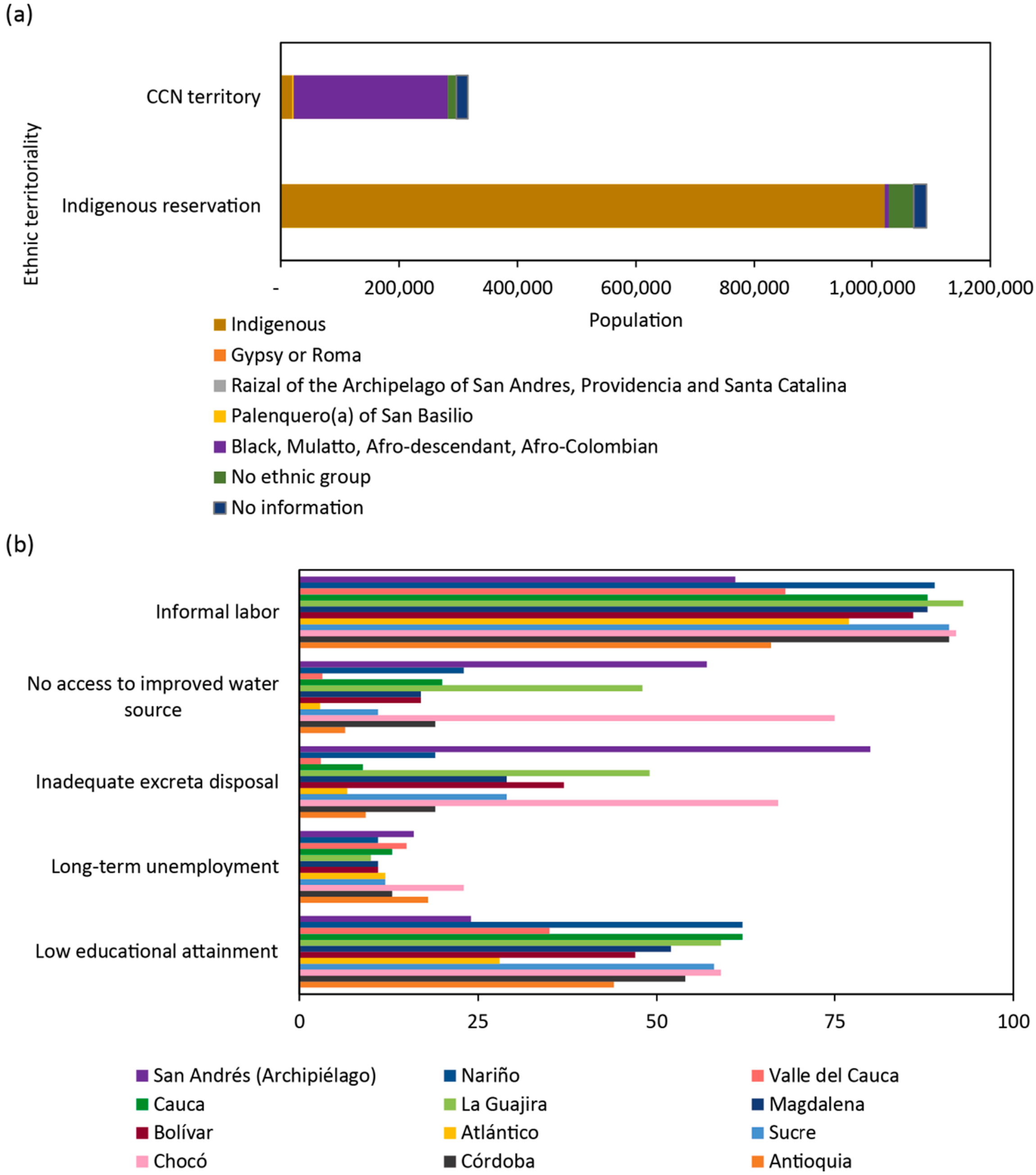

Fig. 7. (a) Population in private households, by ethnic self-recognition and ethnic territoriality. CCN: Collective Territories of Black Communities (Territorios Colectivos de Comunidades Negras) (DANE, 2020c) and (b) Social information Multidimensional Poverty Index 2020 (DANE, 2020d).

affected by the SLR under each of the SSP scenarios, requiring reallocation of families to a secure location in terms of inundation risk. In addition to the financial cost, the social consequences of such a task would be extremely complex.

The population of Colombia contains many different ethnic groups (Fig. 7a) (DANE, 2020a). Given the ethnic territories and the social-cultural value represented, the reallocation of the population in these territories could be more complex and expensive (see Fig. 7b). For example, the departments of Choco and Guajira, which may be affected by sea level rise, have a population of almost 40 % living in indigenous reservations or CCN territory, leading to a special policy in terms of mitigation and adaptation, and reallocation in case this is necessary.

In addition, these departments, and some others, have poverty indicators with values that make the implementation of policies more challenging. The informal labor rate in the departments of Choco and La Guajira are the highest in the country, 92 % and 93 % respectively, and the other affected departments have rates higher than 50 %. This makes tax collection more difficult or non-existing.

Unemployment rates in these departments are also among the highest in the country, which makes it more complicated to adapt to new mitigation and adaptation policies. Moreover, inadequate excreta disposal and no access to treated water sources are also issues that may be worsened by sea level rise.

5. Summary and conclusions

In this study we investigated the economic and social impacts of sea level rise in the coastal zones of Colombia, considering the different SSP scenarios projected by the IPCC report released in 2021. Potential land loss due to the projected sea level rises under different SSP scenarios were delineated. A reconstruction of the sea level rise back to 1870 shows a substantial acceleration in the last century, possibly as a result of global warming which melts land ice and causes ocean expansion (Church & White, 2006). However, the degree of impact on coastal areas depends on the regional and local features such as profile slope, topography, sediment type, wave conditions, tide conditions, meteorological conditions etc. (Orejarena-Rondón et al., 2019). Even though there are severe consequences of sea level rise, in theory, the implementation and success of adaptation policies are fairly uncertain, which leads to a demand for more assessment and consideration (Nicholls & Cazenave, 2010), especially on a regional scale. Therefore, it is essential to conduct local studies that consider all variables to determine the impact of sea level rise on coastal areas, to administer the best mitigation and adaptation measures. The DEM used to analyze the land elevation in our investigation has a resolution of 90 m $\times$ 90 m, which leads to uncertainty in the potential land loss assessment. Naturally, the study evaluates the land which would be below sea level with sea level rise and the behavior in an area of 8,100 m^2 could vary significantly. However, our analysis provides a general scope of the area at potential risk of inundation due to the projected sea level rise. Another limitation is that the information used to determine the sea level rise was obtained by the projections performed by the IPCC in the Sixth Assessment Report, released in 2021, which only forecasted the sea level rise for two meteorological stations in Colombia. Fortunately, the two stations are on both Pacific and Caribbean coastlines. The sea level rise projections were extrapolated spatially and temporally to the whole coastline which leads to a substantial assumption when assessing the potential land loss. Certainly, the sea level rise depends on various local and regional meteorological, climatic, geophysical and other factors and therefore, extreme waves, sea level extremes and surges need to be considered when measuring the impact of the sea level rise.

The results showed a clear trend that the Pacific coast will experience a milder increase in sea level than the Caribbean coast. The increased rates in rising sea levels along the Caribbean coast are likely attributable to natural causes such as tectonic activity or sediment compaction resulting in land subsidence (Restrepo-Ángel et al., 2021).

It should be highlighted that the potential risk assessed in this study does not consider any mitigation measures adopted to protect against the impact of the sea level rise. Each SSP scenario represents a specific pathway the society could take, but special measures, such as dykes to prevent inundation, are not considered in this analysis. Hence, the results should be understood as a signal of the consequences of sea level rise if no actions are undertaken. It should also be mentioned that the uncertainties included in the future SLR projections influence the calculated areas that are under risk of being lost.

To the best of our knowledge, the reported results in this paper offer one of the first detailed analyses of the consequences of the projected sea level rises (released by the IPCC in the Sixth Assessment Report in 2021) with the associated socio-economic impacts on the coastline of Colombia under different climate scenarios. This can be a useful tool and a starting point toward a precise calculation of the environmental, ecological and socio-economic consequences in the region.

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

The sources of all data used in this analysis were cited in the paper and the acknowledgement section.

Acknowledgements

We thank the projection authors for developing and making the sea-level rise projections available, multiple funding agencies for supporting the development of the projections, and the NASA Sea-Level Change Team for developing and hosting the IPCC AR6 Sea-Level Projection Tool. Moreover, we acknowledge the World Climate Research Programme, which, through its Working Group on Coupled Modelling, coordinated and promoted CMIP6. We thank the climate modeling groups for producing and making available their model output, the Earth System Grid Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies who support CMIP6 and ESGF. The funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation, Germany) – Projektnummer 491268466 and the Hamburg University of Technology (TUHH) in the funding programme Open Access Publishing are greatly acknowledged.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2022.100470.

References

Albright, R., Takeshita, Y., Koweek, D.A., Ninokawa, A., Wolfe, K., Rivlin, T., Nebuchina, Y., Young, J., Caldeira, K., 2018. Carbon dioxide addition to coral reef waters suppresses net community calcification. Nature 555 (7697), Art. 7697. https://doi.org/10.1038/nature25968.

Barbier, E.B., 2015. Climate change impacts on rural poverty in low-elevation coastal zones. Estuar. Coast. Shelf Sci. 165, A1–A13.

Blankespoor, B., Dasgupta, S., Laplante, B., 2014. Sea-Level Rise and Coastal Wetlands. Ambio 43 (8), 996–1005. https://doi.org/10.1007/s13280-014-0500-4.

Borchert, S.M., Osland, M.J., Enwright, N.M., Griffith, K.T., 2018. Coastal wetland adaptation to sea level rise: Quantifying potential for landward migration and coastal squeeze. J. Appl. Ecol. 55 (6), 2876–2887. https://doi.org/10.1111/1365-2664.13169.

Church, J.A., White, N.J., 2006. A 20th century acceleration in global sea-level rise. Geophys. Res. Lett. 33 (1).

Coldren, G.A., Langley, J.A., Feller, I.C., Chapman, S.K., 2019. Warming accelerates mangrove expansion and surface elevation gain in a subtropical wetland. J. Ecol. 107 (1), 79–90. https://doi.org/10.1111/1365-2745.13049.

DANE. (2020a). Censo Nacional de Población y Vivienda - CNPV 2018. DANE. http://systema59.dane.gov.co/redcol/CNPV2018/PERSONAS_SOCIAL_Cuadros%20CNPV_2018.htm.

DANE. (2020b). Cuentas Nacionales Anuales. DANE. https://www.dane.gov.co/index.php/estadisticas-por-tema/cuentas-nacionales/cuentas-nacionales-anuales.

DANE. (2020c). Gran Encuesta Integrada de Hogares GEIH. DANE. https://www.dane.gov.co/index.php/estadisticas-por-tema/mercado-laboral/mercado-laboral-por-departamentos.

DANE. (2020d). Indice de Pobreza Multidimensional. DANE. https://www.dane.gov.co/index.php/estadisticas-por-tema/pobreza-y-condiciones-de-vida/pobreza-multidimensional.

Davtalab, R., Mirchi, A., Harris, R.J., Troilo, M.X., Madani, K., 2020. Sea level rise effect on groundwater rise and stormwater retention pond reliability. Water 12, 1129. https://doi.org/10.3390/w12041129.

Fagherazzi, S., Mariotti, G., Leonardi, N., Canestrelli, A., Nardin, W., Kearney, W.S., 2020. Salt Marsh Dynamics in a Period of Accelerated Sea Level Rise. J. Geophys. Res. - Erath Surf. 125 (8) https://doi.org/10.1029/2019JF005200.

Fox-Kemper, B., H. T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S. S. Drijfhout, T. L. Edwards, N. R. Golledge, M. Hemer, R. E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I. S. Nurhati, L. Ruiz, J-B. Sallée, A. B. A. Slangen, Y. Yu, 2021, Ocean, Cryosphere and Sea Level Change. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In press.

Funakawa, S., Kosaki, T., 2007. Potential risk of soil salinization in different regions of Central Asia with special reference to salt reserves in deep layers of soils. Soil Sci. Plant Nutr. 53 (5), 634–649.

Garner, G. G., T. Hermans, R.E. Kopp, A.B.A. Slangen, T.L. Edwards, A. Levermann, S. Nowikci, M.D. Palmer, C. Smith, B. Fox-Kemper, H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T. L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J-B. Sallée, Y. Yu, L. Hua, T. Palmer, B. Pearson, 2021. IPCC AR6 Sea-Level Rise Projections. Version 20210809. PO.DAAC, CA, USA. Dataset accessed [2021-12-13] at https://podaac.jpl.nasa.gov/announcements/2021-08-09-Sea-level-projections-from-the-IPCC-6th-Assessment-Report.

Hassani, A., Azapagic, A., Shokri, N., 2021. Global predictions of primary soil salinization under changing climate in the 21st century. Nat. Commun. 12, 6663. https://doi.org/10.1038/s41467-021-26907-3.

Herbert, E.R., Boon, P., Burgin, A.J., Neubauer, S.C., Franklin, R.B., Ardón, M., Hopfensperger, K.N., Lamers, L.P., & Gell, P., 2015. A global perspective on wetland salinization: Ecological consequences of a growing threat to freshwater wetlands. Ecosphere, 6, 10, 1–43.

Magnan, A.K., Oppenheimer, M., Garschagen, M., Buchanan, M.K., Duvat, V.K.E., Forbes, D.L., Ford, J.D., Lambert, E., Petzold, J., Renaud, F.G., Sebesvari, Z., van de Wal, R. S. W., Hinkel, J., & Pörtner, H.-O., 2022. Sea level rise risks and societal adaptation benefits in low-lying coastal areas. Sci. Reports, 12, 1, Art. 1. https://doi.org/10.1038/s41598-022-14303-w.

Martyr-Koller, R., Thomas, A., Schleussner, C.F., Nauels, A., Lissner, T., 2021. Loss and damage implications of sea-level rise on Small Island Developing States. Curr. Opin. Environ. Sustain. 50, 245–259.

Masson-Delmotte, V., Zhai, P., Priani, A., Connors, S.L., Péan, C., Berger, S., 2021. IPCC, 2021: Climate Change 2021: The Physical Science Basis. ContrIbutIon of WorkIng Group I to the SIxth Assessment Report of the Intergovernmental Panel on ClImate Change. Cambridge University Press, Cambridge, UK.

McGranahan, G., Balk, D., Anderson, B., 2007. The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. Environ. Urban. 19 (1), 17–37. https://doi.org/10.1177/0956247807076960.

Mitsch, W.J., Bernal, B., & Hernandez, M.E., 2015. Ecosystem services of wetlands. In: International Journal of Biodiversity Science, Ecosystem Services & Management (Bd. 11, Nummer 1, S. 1–4). Taylor & Francis.

Moftakhari, H.M., Salvadori, G., AghaKouchak, A., Sanders, B.F., Matthew, R.A., 2017. Compounding Effects of Sea Level Rise and Fluvial Flooding, Proceedings of the National Academy of Sciences, 114 (37), 9785–9790, http://doi.org/10.1073/pnas.1620325114.

Montgomery, M., 2007. United Nations Population Fund: State of World Population 2007: Unleashing the Potential of Urban Growth. Popul. Dev. Rev. 33 (3), 639–641.

Nicholls, R.J., Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. Science (New York, N.Y.) 328, 1517–1520. https://doi.org/10.1126/science.1185782.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. 42, 169–180.

Oppenheimer, M., Alley, R.B., 2016. How high will the seas rise? Science 354 (6318), 1375–1377. https://doi.org/10.1126/science.aak9460.

Orejarena-Rondón, A.F., Sayol, J.M., Marcos, M., Otero, L., Restrepo, J.C., Hernández-Carrasco, I., & Orfila, A., 2019. Coastal impacts driven by sea-level rise in Cartagena de Indias. Front. Marine Sci., 6, 614.

Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., & Dasgupta, P., 2014. Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Ipcc.

Perry, C.T., Alvarez-Filip, L., Graham, N.A.J., Mumby, P.J., Wilson, S.K., Kench, P.S., Manzello, D.P., Morgan, K.M., Slangen, A.B.A., Thomson, D.P., Januchowski-Hartley, F., Smithers, S.G., Steneck, R.S., Carlton, R., Edinger, E.N., Enochs, I.C., Estrada-Saldívar, N., Haywood, M.D.E., Kolodziej, G., Macdonald, C., 2018. Loss of coral reef growth capacity to track future increases in sea level. Nature 558 (7710), Art. 7710. https://doi.org/10.1038/s41586-018-0194-z.

Restrepo-Ángel, J.D., Mora-Páez, H., Díaz, F., Govorcin, M., Wdowinski, S., Giraldo-Londoño, L., Tosic, M., Fernández, I., Paniagua-Arroyave, J.F., Duque-Trujillo, J. F., 2021. Coastal subsidence increases vulnerability to sea level rise over twenty first century in Cartagena, Caribbean Colombia. Sci. Rep. 11 (1), Art. 1. https://doi.org/10.1038/s41598-021-98428-4.

Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., & Fricko, O., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob. Environ. Change, 42, 153–168.

Shokri-Kuehni, S.M.S., Raaijmakers, B., Kurz, T., Or, D., Helmig, R., Shokri, N., 2020. Water table depth and soil salinization: From pore-scale processes to field-scale responses. Water Resour. Res. 56 https://doi.org/10.1029/2019WR026707 e2019WR026707.

The World Bank (2022), Population, total - colombia. (n.d.). Retrieved November 23, 2022, from https://data.worldbank.org/indicator/SP.POP.TOTL?locations=CO.

van den Hurk, B., Bisaro, A., Haasnoot, M., Nicholls, R.J., Rehdanz, K., Stuparu, D., 2022. Living with sea-level rise in North-West Europe: Science-policy challenges across scales. Clim. Risk Manag. 35, 100403 https://doi.org/10.1016/j.crm.2022.100403.

Yamazaki, D., Ikeshima, D., Tawatari, R., Yamaguchi, T., O'Loughlin, F., Neal, J.C., Sampson, C.C., Kanae, S., Bates, P.D., 2017. A high-accuracy map of global terrain elevations. Geophys. Res. Lett. 44 (11), 5844–5853. https://doi.org/10.1002/2017GL072874.