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RESEARCH ARTICLE

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Sea-level rise induced change in exposure of low-lying coastal land: implications for coastal conservation strategies

Rémi Thiéblemont^{1*}, Gonéri le Cozannet¹, Jérémy Rohmer¹, Adrien Privat², Romain Guidez¹, Caterina Negulescu¹, Xénia Philippenko¹, Arjen Luijendijk³, Floris Calkoen³ and Robert J. Nicholls⁴

Abstract

Coastal erosion and flooding are projected to increase during the 21st century due to sea-level rise (SLR). To prevent adverse impacts of unmanaged coastal development, national organizations can apply a land protection policy, which consists of acquiring coastal land to avoid further development. Yet, these reserved areas remain exposed to flooding and erosion enhanced by SLR. Here, we quantify the exposure of the coastal land heritage portfolio of the French Conservatoire du littoral (CdL). We find that 30% (~40%) of the CdL lands owned (projected to be owned) are located below the contemporary highest tide level. Nearly 10% additional surface exposure is projected by 2100 under the high greenhouse gas emissions scenario (SSP5-8.5) and 2150 for the moderate scenario (SSP2-4.5). The increase in exposure is largest along the West Mediterranean coast of France. We also find that CdL land exposure increases more rapidly for SLR in the range of 0–1 m than for SLR in the range 2–4 m. Thus, near-future uncertainty on SLR has the largest impact on CdL land exposure evolution and related land acquisition planning. Concerning erosion, we find that nearly 1% of CdL land could be lost in 2100 if observed historical trends continue. Adding the SLR effect could lead to more than 3% land loss. Our study confirms previous findings that CdL needs to consider land losses due to SLR in its land acquisition strategy and start acquiring land farther from the coast.

Keywords Climate change, Coastal hazards, Sea-level rise, Coastal conservation agency, Shoreline

1 Introduction

Human development is increasingly shaping coastal areas across the world (Brown et al. 2014; Neumann et al. 2015). If poorly managed, such development can damage coastal ecosystems and their services, reduce the coastal landscape value, and ultimately affect food production,

tourism, and coastal communities (IPBES 2019). One of the approaches available to prevent such adverse impacts consists in purchasing coastal land, in order to avoid its development or restore it. This can be performed by organizations such as the National Trust in the United Kingdom, the National Coastal Zone Management Program in the USA, or the Coastal Conservation Agency in France (Meur-Férec 1997).

Due to climate change, additional threats are now emerging in coastal areas. This includes the warming of coastal waters, changing waves, current and storms, and sea-level rise (SLR) (Cooley et al. 2022). Among these factors, SLR is projected to have the largest impacts on extreme sea levels in Europe (Vousdoukas et al. 2017). SLR is therefore considered a major issue for coastal conservation agencies. Specifically, it is projected to cause

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coastal erosion, flooding and inundation, and the associated land losses can include land owned by coastal conservation agencies (Clus-Auby et al. 2006). This raises the following question: to what extent might strategies (and their associated time horizon) from coastal conservation agencies be affected by sea-level rise?

In this study, we focus on the case of the Coastal Conservation Agency (Cdl) in France which was founded in 1975. Cdl currently protects more than 2,000 km² at 800 sites in Mainland France and overseas. This comprises 1,150 km² of land acquisitions, with the balance comprising public domain handovers. It currently owns 13% of the coastline length in France and aims to grow this to 25% by 2050 and acquire 3,200 km² of land to protect (Conservatoire du littoral 2015). To ensure this objective is met, Cdl has defined a strategic approach to ensure that new acquisitions are consistent with its long-term objectives. Yet, coastal areas currently owned by Cdl are widely vulnerable to SLR: it has been estimated that approximately 20% of the surface area owned by the Cdl in the early 2000(s) could be lost given a 44 cm SLR scenario by 2100 (Clus-Auby et al. 2006).

Here, we go a step further by assessing specific decisions relevant to the Cdl in mainland France in terms of its coastal land acquisition strategy, revisiting the exposure of the coastal areas currently owned by Cdl, and performing a first assessment of the current land acquisition strategy. This is done by (1) assessing the decision problems of the Cdl through a literature survey and bilateral workshops; and (2) assessing present day and future exposure of the land areas owned by Cdl, considering the most recent regional sea level projections of the Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report (AR6).

2 Material & methods

2.1 Assessment of the decision problem

The literature on climate services for coastal adaptation suggests that decision-oriented information can best support adaptation (Le Cozannet et al. 2017; Hinkel et al. 2019; Kopp et al. 2019; Lawrence et al. 2021; Simm et al. 2021; Durand et al. 2022). Here, we performed bilateral meetings with the Cdl in order to assess more precisely their decision problem and the information needed to inform their decisions. These meetings were conducted as unstructured interviews and were held between 2018 and 2021 in visio conference, during the early stage of the H2020-PROTECT project (<https://protect-slr.eu/>; Capar et al. 2020). The aim of the meeting was to identify decision problems on coastal adaptation that the Cdl is facing (see Capar et al. 2020). They involved two researchers at BRGM and up to two persons working at the Headquarters of Cdl and involved in the Adapt'O project exploring

and experimenting adaptive coastal management on pilot sites of the CdL (<https://www.lifeadapto.eu/home.html>). These bilateral meetings were complemented with a review of strategic documents, especially the 2015–2050 Cdl strategy (Conservatoire du littoral 2015).

2.2 Exposed land

Following these meetings, the Cdl provided three georeferenced vector datasets that correspond to different types of land relevant to their long-term strategy to own 25% of the French coastline length and near 3,200 km² of land to protect (Conservatoire du littoral 2015).

The Protected Area dataset refers to the land and real estate already owned by the Cdl. It contains ~55,000 plots of land that have a median area of ~2,000 m², a 99th percentile area of ~332,000 m² for a total area (i.e. national scale) of ~1,150 km². It excludes 850 km² additional land donated to Cdl, which are not considered in the strategy. The Authorized Perimeter dataset corresponds to the land area that the Cdl is authorized to acquire. It represents slightly less than 800 plots of land but which are far more spatially extended than the Protected area with a median area of ~927,000 m² and a total area of 2,650 km². Finally, the Strategy 2015–2050 identifies areas that are considered for future acquisitions, in order to meet the strategic objective of protecting 25% of the coastline length by 2050 and near 3,200 km² of land. This dataset is even more extended spatially than the two other datasets with a total area of 4,823 km² and a median area of 310,000 m² for ~2,830 plots of land. Figure 1 shows the distribution of the spatial extent of the plot of land per coastal NUTS (Nomenclature of Territorial Units for Statistics) 3 level region (i.e. less than 800,000 inhabitants).

Hereinafter, these three land datasets will be referred to as (1) *Protected Area*, (2) *Authorized Perimeter* and (3) *Strategy 2015–2050*, respectively.

2.3 Change in low-lying area exposure

We assess change in exposure by identifying areas whose elevation is below the highest astronomical tide today and in the future for different SLR scenarios. This method is static as it does not account for the available water volume nor for the dynamics of the water flow. It is therefore expected to overestimate the extent of areas affected by coastal hazards, but, on the other hand, allows appraising the maximum extent of areas potentially exposed. This approach is a prerequisite analysis for all coastal Risk Prevention Plans in France before developing advanced hydrodynamical simulations. Note that our approach is slightly different from the “bathtub” method widely used in global assessments (e.g. Lichter et al. 2011; Hinkel et al. 2014; Vafeidis et al. 2019; Rohmer et al. 2021), as we do not consider hydraulic connectivity (Bates et al. 2005;

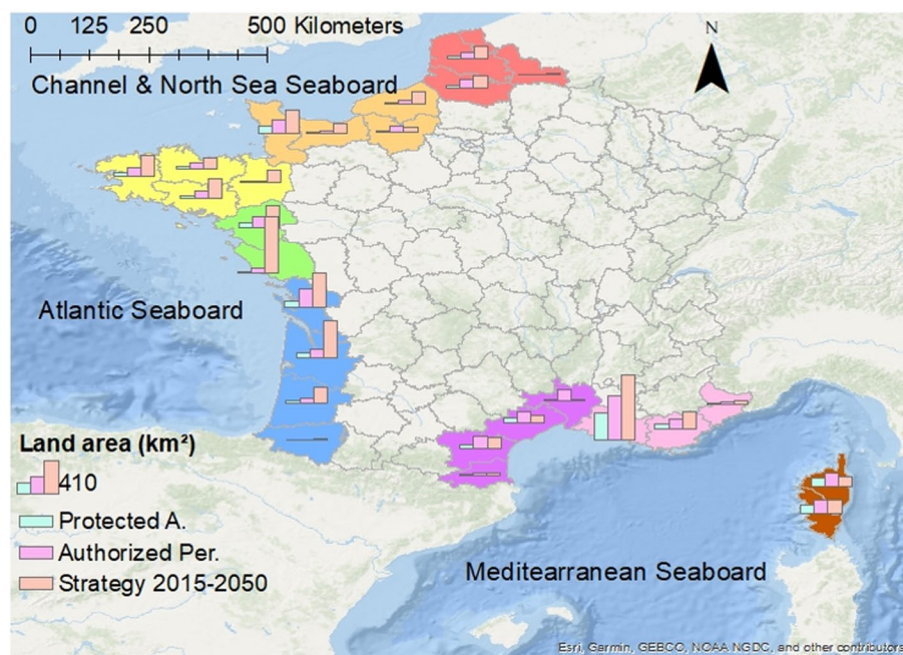


Fig. 1 Distribution of Protected Area, Authorized Perimeter and Strategy 2015–2050 plots per French NUTS3 coastal region. Uniform colours indicate the NUTS1 level (i.e., 3 to 7 million averaged population)

Poulter and Halpin 2008). We found anyhow that including hydraulic connectivity has no significant influence on our results (see Section 4.1).

In this study, low-lying areas are identified using the digital terrain model provided by the French National Geographic Institute (IGN) and their program RGE-Altitude (<https://geoservices.ign.fr/rgealti>). This dataset provides the very high-resolution (~1 m) coastal topography retrieved from LiDAR measurements (airborne laser) available at the National scale in France. For mainland France (including Corsica), data are provided in the datum RGF93 with a vertical accuracy of 0.2 m. The coastline is identified from the Histolitt V2 product (Shom - Institut Géographique National (IGN) (2010)). These data are part of the wider Litto3D program operated by Shom and IGN.

Figure 2 describes the workflow used to identify Cdl lands in low-lying areas. As a reference, we used the high-resolution topography datasets to map land regions (i.e. landward of the coastline) that are located below the contemporary (i.e. for a mean SLR anomaly of 0 m) highest astronomical tide (Tellez-Arenas et al. 2018). Contemporary refers here to a period that span ~15 years until 2016: this means that the baseline mean sea-level calculated for mainland France corresponds to the mean sea-level state representative of the period 2000–2014. The mapping at highest astronomical tide is then repeated for a mean SLR from 0 to 4 m at 0.5 m steps. These maps

can be visualised at <https://sealevelrise.brgm.fr/slr/>. Note that we assume no change of tidal range with SLR. Low-lying areas are then intersected with Cdl land vector datasets (Protected Area, Authorized Perimeter and Strategy 2015–2050). Hereafter, exposure is quantified as the surface extent of Cdl land comprised within low-lying areas below the highest astronomical tide.

The example displayed in Fig. 2 illustrates the case of Protected Area plots located in the municipalities of “La Brée-les-Bains” and “Saint-Georges d’Oléron” on Oléron Island. The exposed land identified here are consistent with the zones identified at risk of marine flooding for various scenarios used in the Coastal Risk Prevention Plan (Artelia, 2016, https://www.nouvelle-aquitaine.developpement-durable.gouv.fr/IMG/pdf/cc-pprn-ile-oleron_web.pdf).

2.4 Change in coastal land area by erosion

We assess future sandy shoreline changes by extrapolating recent shoreline change trends and superimposing the effects of SLR considering the Bruun rule (Bruun 1962). This approach does not capture the effects of changing nearshore sediment transport, whether due to natural processes or human interventions, but it is applicable to SLR at broad scale (Vitousek et al. 2017; Toimil et al. 2020). Despite longstanding criticism (Cooper and Pilkey 2004) and ongoing debates about its applicability (Vousdoukas et al. 2020; Cooper et al. 2020), the Bruun

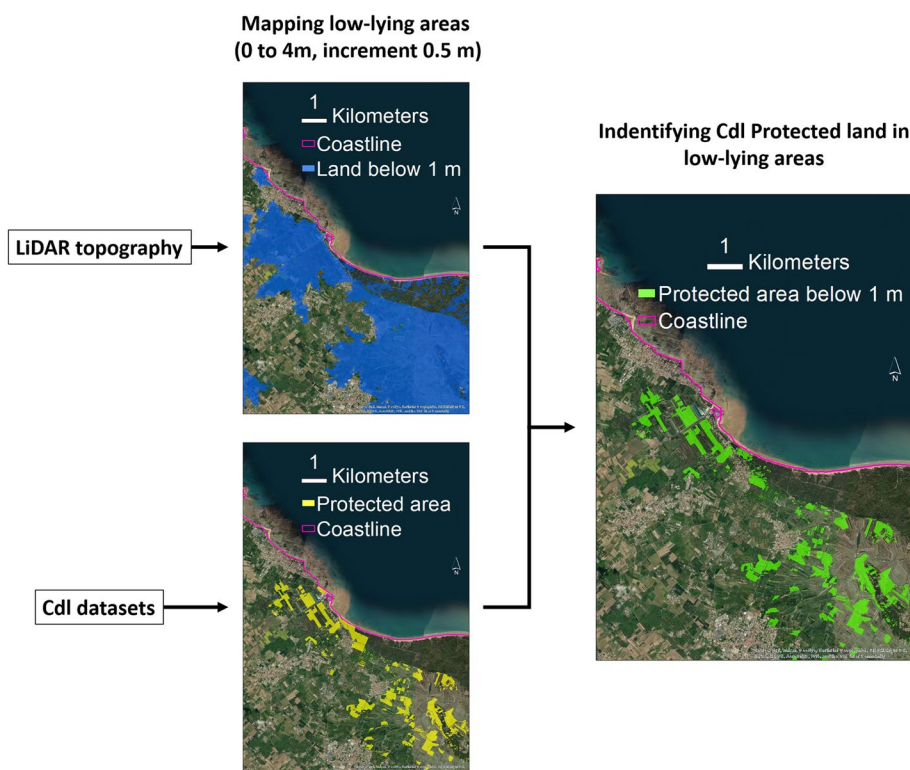


Fig. 2 Workflow for identifying and quantifying Cdl land in low-lying areas. Here, the example displays the North-East part of Oléron Island, located in the Atlantic seaboard of France and assumes a SLR of 1 m compared to the current mean sea-level

rule continues to be used in complex local erosion assessments (D’Anna et al. 2021), probably due to the absence of credible, broad-scale alternatives for sandy beach erosion projections.

To detect coastal land located near sandy coasts, we used the EUROSION coastal database (<https://www.eea.europa.eu/en/datahub/datahubitem-view/ba6d7fe6-c79f-48c7-b738-f78260730538>). This pan-European database was developed to support the assessment of coastal erosion status and trends (see Supplementary material A.1 for details). Specifically, we rely on the description of the coastline’s geomorphology and geology to identify sandy coasts (see Thiéblemont et al. 2019 for details). Since EUROSION’s shoreline position is not accurately georeferenced, Histolitt V2 is used as the reference instead. Finally, for shoreline trends assessment, EUROSION estimates are representative of trends in the 1980’s and 1990’s, and remain qualitative as they only provide information on shoreline change behaviour; i.e. stable, retreat or accretion. Therefore, we used the Shoreline-Monitor database which considers the observed shoreline trends of the first two decades of the 21st century based on satellite measurements as well (Luijendijk et al. 2018, Supplementary material A.2) (<http://shoreline-monitor.deltares.nl>).

The workflow for estimating shoreline change impact on Cdl land area is sketched in Fig. 3. Starting from the Cdl vector datasets that identify land areas of interest, we first use the geomorphology layer of the EUROSION database to identify land that is located less than 500 m from a sandy segment. For the Protected Area dataset for instance, this represents roughly one quarter of the total number of plots of land (~12,000 out of 55,000).

Once identified, for each plot we select the Shoreline-Monitor transects that are within 500 m distance of the plot perimeter (transects on Fig. 3). As shown in Fig. 3, the resolution of the generalized OpenStreetMap 2016 coastline (used in the ShorelineMonitor, black dots) does not allow a perfect match with the high-resolution coastline provided by Histolitt V2 (red line). This is adjusted by translating the coastline position of ShorelineMonitor along the transect until crossing the Histolitt V2 reference coastline (red dots). Finally, the shoreline retreat is calculated for each transect (using various coastline retreat models – see hereinafter) and then used to compute an area of land loss (transparent orange area). This area of land loss is drawn as a band, which is collinear to the shoreline, and from which the distance to the shoreline is equal to the mean of the retreat computed over all transects within the buffer domain (black perimeter).

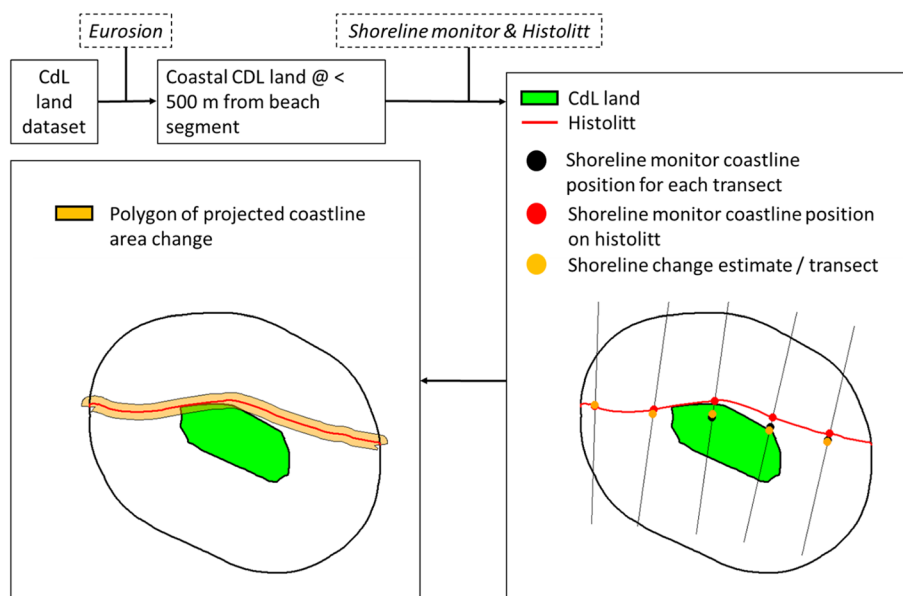


Fig. 3 Workflow for shoreline change estimates and impact on CdL land area

Note that the shoreline retreat is estimated only if more than 90% of the transects are flagged as sandy beaches by the ShorelineMonitor.

To estimate shoreline retreat for each transect, several shoreline recession model were tested in order to reflect the deep uncertainty inherent to such projection, especially over extended spatial domains (Thiéblemont et al. 2021). The shoreline change models that we tested are derived from Eq. 1:

$$\Delta S = n \cdot T_x + \frac{SLR}{\tan \beta} \tag{1}$$

where ΔS indicates the shoreline change, n is the number of years relative to the time reference, T_x is the historical shoreline trend provided by the ShorelineMonitor, and $SLR/\tan \beta$ quantifies the contribution of SLR to shoreline changes, which takes the form of the Bruun rule (Bruun 1962). Our first approach consists in only considering the first term ($n \cdot T_x$) (i.e. extrapolating the recent historical trend toward the future), while for the remaining ones, we superimposed the effect of SLR testing three different beach slopes values ($\tan \beta$): 10%, 1% and the nearshore slopes retrieved by Athanasiou et al. (2019).

2.5 Sea-level projections

Climate change induced regional SLR relies on the mean sea-level projections developed for the IPCC AR6 (Fox-Kemper et al. 2021; Garner et al. 2021) that can be extracted from a 1°deg/1°deg (lon/lat) grid or at tide gauges at <https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool>. These projections include the

sterodynamic effect (i.e. the thermal expansion and ocean dynamic sea-level), contemporary mass redistribution (i.e. glaciers, Greenland and Antarctic ice-sheets, and land-water storage) and vertical land motions due to glacial isostatic adjustment and other local drivers. Gravitational, Rotational and Solid-Earth Deformation effects associated with contemporary mass redistribution (GRD effects; Gregory et al. (2019)) are computed from the sea-level equation solver of Slangen et al. (2014). The GRD effects consider the non-spatially uniform relative sea-level induced by glaciers, ice-sheets and land-water storage mass redistribution. Details on how AR6 regional mean sea level projections were obtained are provided in the Supplementary material A.3.

In our study, we restrict the analysis to 4 Shared Socio-Economic Pathways (SSPs) or scenarios (Riahi et al. 2017): SSP1-2.6 (Sustainability - low greenhouse gases (GHG) emissions), SSP2-4.5 (Middle of the road - intermediate GHG emissions), SSP5-8.5 (Fossil-fueled Development – high GHG emissions) and SSP5-8.5 low-confidence (high-end scenario considering ice-sheet collapse). We also consider spatially uniform regional sea-level projections per seaboard; i.e. The Channel and North Sea (-3°E/49°N), Atlantic (-3°E/45°N) and Mediterranean (5°E/42°N) (Fig. 1). Mean sea-level projections used in this study are shown in Table 1. Note that the baseline period 1995–2014 for the mean sea-level projections provided by the AR6 is close to the baseline period used to derive the highest astronomical tide level (2000–2015) (see §2.2). Hereafter, both are assumed to be aligned.

Table 1 Median and likely range of regional mean sea-level change (expressed in meters) in 2050, 2100 and 2150 (reference period 1995–2014) for four SSP scenarios and the three mainland France seaboards

	2050			2100			2150		
	Chan.	Atl.	Med.	Chan.	Atl.	Med.	Chan.	Atl.	Med.
SSP1-2.6	0.19 [0.11–0.29]	0.2 [0.12– 0.30]	0.21 [0.11–0.32]	0.41 [0.24–0.63]	0.44 [0.26–0.65]	0.46 [0.25–0.7]	0.58 [0.28–0.97]	0.63 [0.32–1.02]	0.67 [0.32–1.10]
SSP2-4.5	0.21 [0.13–0.30]	0.22 [0.14–0.31]	0.22 [0.13–0.33]	0.53 [0.36–0.77]	0.55 [0.38–0.79]	0.58 [0.37–0.85]	0.82 [0.49–1.29]	0.86 [0.53–1.33]	0.92 [0.53–1.43]
SSP5-8.5	0.23 [0.15–0.32]	0.24 [0.16–0.33]	0.25 [0.16–0.35]	0.72 [0.50–1.03]	0.75 [0.55–1.05]	0.77 [0.54–1.09]	1.19 [0.74–1.82]	1.24 [0.81–1.87]	1.29 [0.82–1.94]
SSP5-8.5 L	0.23 [0.14–0.35]	0.24 [0.16–0.37]	0.25 [0.15–0.40]	0.82 [0.50–1.28]	0.85 [0.55–1.34]	0.88 [0.54–1.42]	1.85 [0.74–4.99]	1.92 [0.81–5.05]	1.96 [0.82–5.00]

In 2050, mean sea-level projections show little difference between scenarios and seaboards with a median estimated rise between 0.2 and 0.25 m. Note that this projected rise over a 30-year period is equivalent to the mean SLR measured since 1880 (i.e. over 140 years). Divergence between scenarios is well pronounced in 2100 with a difference of ~0.4 m of median mean SLR between the SSP1-2.6 and SSP5-8.5 low confidence scenarios. In 2100, regional differences along French coasts start to emerge, with higher projected SLR along the Mediterranean coast than along the Channel/North Sea coast by ~5 cm. By 2150, SSP5-8.5 and SSP5-8.5 low-confidence scenarios show both median mean-sea level estimates above 1 m with large uncertainties for the low-confidence scenario, which shows a likely range (i.e. greater than 66% probability) that could reach ~5 m.

3 Results

3.1 The decision problem

The bilateral meetings and literature surveys focused on the strategic objectives of the Cdl (Table 2). In

Table 2 Strategic objectives of the Cdl identified in the review. All these specific objectives can be compromised by sea-level rise

Objectives	
Overarching goal	Preservation of the French coast.
Specific objectives	1- Conservation of emblematic coastal areas, to ensure their transfer to future generations 2- Preservation of the natural and historical coastal heritage to support the attractiveness of coastal regions in the future; this includes the prevention of urban sprawl and actions to maintain natural processes; 3- Social well-being by guaranteeing fair and equal access to coastal areas for all 4- The protection of people and goods against extreme climatic phenomena by creating a buffer zone between the sea and human assets

quantitative terms, these objectives are materialized in the goal of protecting 25% of French shoreline by owning the correspondent waterfront areas by 2050 (Conservatoire du littoral 2015).

The interviews and review of documents also showed that the Cdl considers many adaptation options, depending on the coastal sites, including protection, “do-nothing” and managed realignment (Doze 2015). Furthermore, the Cdl is experimenting with soft management approaches that allow land losses but also lower costs of engineering protection and maintain natural landscape values (Bazin and Olivry 2017). Therefore, it should not be assumed that terrestrial areas currently owned by the Cdl should necessarily be terrestrial area protected in the future.

Considering these aspects, the Cdl is concerned with defining a land acquisition strategy that allows achievement of its objectives (Table 2), while anticipating future land losses resulting from its coastal management approach. This is the first decision problem identified during the bilateral meetings and documents analysis (Section 2.1). For completeness, we precise that the second decision problem, which is outside of the scope of this paper, is about informing the management options of particular sites, especially those exploring adaptive coastal management strategies (Capar et al. 2020).

The land acquisition decisions that are considered now are represented by the authorized perimeter and the acquisition strategy 2015–2050. A first step to inform these decisions about SLR consists of identifying regions where areas are threatened, in order to define land acquisition priorities. This is presented in the next subsections.

Cdl performs environmental, social and organizational assessments every 10 years. These assessments aim to identify natural or semi-natural lands in need of protection and/or with high potential landscape, heritage and biodiversity value, as well as to update

a long-term strategy and establish the future zones where Cdl will be allowed to buy land. Hence, they provide decision points for adjusting the land acquisition strategy.

3.2 Change in low-lying area exposure

3.2.1 Mainland national scale

Considering the contemporary mean sea-level conditions, we estimated that 30%, 33% and 42% of Protected Area, Authorized Perimeter and Strategy 2015–2050 lands are located below the high tide level, respectively. Table 3 further indicates how land area exposure is expected to change with SLR for the three land types. By 2050, a median increase of 4 to 5% (2 to 3%) in the total area exposed to SLR is projected in comparison with the recent past situation for the Protected Area and Authorized Perimeter (Strategy 2015–2050). In 2050, Cdl land exposure changes appear to be little depending on the SSP scenario. The likely ranges span ~2.5 to 6.5% for the Protected Area and Authorized Perimeter and ~1.5 to 4.8% for the Strategy 2015–2050. In 2100, differences between scenarios start being more pronounced, as for instance shown for the Protected Area case where the less impactful scenario results in 7.7 (4.8–10.1) % increase against

11.5 (8.7–14) % increase for the low confidence high impact scenario. Expressed in relative changes, the results are relatively insensitive to the type of land of interest, although the strategy 2015–2050 plots appear somewhat less exposed than the two others. In comparison, near 10% land exposure increase will translate into 110, 260 and 480 km² for the Protected Area, Authorized Perimeter and Strategy 2015–2050 datasets, respectively.

Considering the high-end scenario (i.e. SSP5-8.5 low confidence), the increase in exposure could be potentially very large (although unlikely) in 2150. Indeed, the upper bound of the likely range (83rd percentile) is 30% for the Authorized Perimeter and almost 40% for the Protected Area. This reflects how the current deep uncertainties on ice-sheet processes and their related influence on mean sea-level projections (Bamber et al. 2019; Edward et al. 2021; DeConto et al. 2021) can affect long-term coastal impacts and their uncertainty.

In the following section, we repeat the analysis but at the regional scale.

3.2.2 Regional scale

Figure 4 shows an example of how land exposure evolves with SLR for two NUTS1 regions: Bretagne (Atlantic seaboard) and Occitanie (Mediterranean seaboard) (see also Fig. 1). The example focuses on Protected Area. In both regions, coastal land exposure shows a very distinct response to sea-level rise.

In Bretagne, exposure of plots of Protected Area to SLR increases linearly but remains overall small. In the Finistère department for instance, the protected domain exposure increases from 20% (of the total area of Cdl land in this department) currently located below the highest tide level to 40% for a 4 m SLR. The smallest increase is found for the Cotes d'Armor, for which, the increase goes from 8% (contemporary) to 14% (4 m SLR). The bottom panel allows bringing the SLR levels changes back to actual SSP scenarios and timeslices. Up to 2100, most projections show SLR and associated likely range that do not exceed 1 m (except for the SSP5-8.5 low-confidence), which translates in quite modest increase of exposure of Cdl lands, with a maximum of 8% increase between 0 and 1 m for Morbihan and Finistère. Considering high-impact scenarios in 2150 (i.e. SSP5-8.5 mid and low confidence) could lead to SLR increase larger than 2 m with a corresponding exposure increase of more than 10%.

In Occitanie, the increase in exposure of Cdl land to SLR shows a behaviour that differs strongly from Bretagne, with a very sharp increase between 0 (e.g. contemporary) and 2 m SLR followed by a plateau beyond 2 m. Such an evolution is found consistently for the

Table 3 Median and likely range of Cdl land area exposure change in 2050, 2100 and 2150 (reference period 1995–2014) for the four SSP scenarios across mainland France. Changes are expressed in % increase as compared to the national scale land area considering a reference of 0 m; i.e. under current mean sea-level state. As an example, 30% of the Protected Area land is under the high-tide level and this exposure would increase to 30 + 4.1 = 34.1% under the median SSP1-2.6 scenario in 2050 (hence a 13.7% relative increase compared to current state)

	2050	2100	2150
Protected Area (in %) (current: 30%)			
SSP1-2.6	4.1 [2.4–5.9]	7.7 [4.8–10.1]	9.9 [5.9–12.6]
SSP2-4.5	4.3 [2.6–6.0]	9.0 [6.6–11.2]	11.7 [8.6–14.0]
SSP5-8.5	4.7 [3.2–6.3]	10.8 [8.7–12.7]	13.5 [11.1–15.5]
SSP5-8.5 Low Conf.	4.8 [3.1–7.0]	11.5 [8.7–14.0]	15.6 [11.1–21.5]
Authorized Per. (in %) (current: 33%)			
SSP1-2.6	3.8 [2.2–5.4]	7.2 [4.5–9.9]	9.6 [5.5–12.9]
SSP2-4.5	4.0 [2.4–5.6]	8.7 [6.2–11.2]	11.7 [8.2–14.6]
SSP5-8.5	4.3 [2.9–5.9]	10.6 [8.3–12.9]	14.0 [11.0–16.5]
SSP5-8.5 Low Conf.	4.4 [2.8–6.5]	11.5 [8.3–14.6]	16.6 [11.0–30.4]
Strategy 2015–2050 (in %) (current: 42%)			
SSP1-2.6	2.7 [1.6–4.0]	5.4 [3.3–7.6]	7.3 [4.1–10.2]
SSP2-4.5	2.9 [1.8–4.1]	6.6 [4.6–8.7]	9.2 [6.2–11.7]
SSP5-8.5	3.2 [2.1–4.3]	8.2 [6.3–10.2]	11.2 [8.6–13.6]
SSP5-8.5 Low Conf.	3.2 [2.1–4.8]	9.0 [6.3–11.7]	13.7 [8.6–19.8]

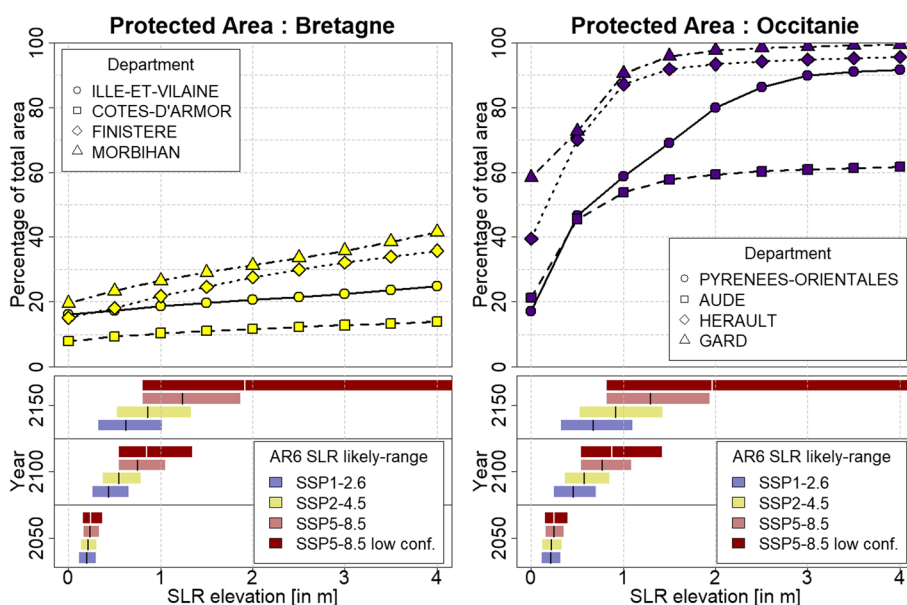


Fig. 4 Evolution of the Cdl low-lying land exposure (expressed in % of total land area per NUTS3 region) as a function of SLR from 0 to 4 m. Left (right) panel shows the results for the NUTS1 region Bretagne (Occitanie) and within each panel, results are detailed to the NUTS3 levels. The bottom panels report the corresponding SLR projections and their likely range for 4 scenarios (SSP1-2.6, SSP2-4.5, SSP5-8.5 and SSP5-8.5 low confidence) and 3 timeslices (2050, 2100 and 2150)

four NUTS3 departments (Pyrénées-Orientales, Aude, Hérault and Gard). These results stress that for Occitanie, increase in exposure of Cdl lands is more sensitive to SLR in the range 0–2 m than beyond. Further examples of land exposure evolution with SLR for all regions and all types of plots are available in the Supplementary material B.1.

Figure 5 summarizes the Cdl Protected Area changes in exposure for all mainland France NUTS3 regions, 4 scenarios and 3 timeslices compared to the baseline (i.e. contemporary exposure). Figure 5a shows the baseline land exposure: i.e. the percentage of total land area per NUTS3 region that is located below the highest tide level under contemporary mean-sea level. This baseline exposure strongly varies from a NUTS3 region to another and 5 of them have already 50% of their Protected Area plots of land located below the highest tide level (i.e. Seine-Maritime, Eure, Vendée, Charente Maritime and Gard). Note however that these coastal departments have a rather small total area of Protected land (gold curve).

The projections show that in 2050 (Fig. 5b), the Cdl protected area changes in exposure should increase by less than 5% (of the total land area per NUTS3) in most regions and independently of the scenario. Along the west Mediterranean coast though, exposure is found to increase by 5 to 20%. This result is consistent with Fig. 4, where even modest SLR increases can have a large impact

on exposure in Occitanie. It also highlights that national scale assessment does not allow reflecting the substantial regional diversity of land exposure change.

In 2100, the overall pattern is similar to that of 2050 but the exposure is further amplified: exposure increase is lower than 10% in most regions but for west Mediterranean coast where regions with exposure increasing to more than 20% and up to 50% are found. The dependence to scenarios is becoming important in 2100, in particular in the most exposed regions (i.e. West-Med). Few regions display almost no exposure increase compared to 2050 – e.g. Pyrénées Atlantique or Alpes Maritime – these are regions characterized by mountainous inland and have a very small area of Cdl Protected land (Fig. 5a). Note that les Landes in south western France along the Atlantic coast shows a particularly large enhancement of exposure between 2050 and 2100 compared to other departments. This is consistent with the sudden sharp increase in exposure found between 0.5 and 1 m SLR (see Supplementary material B.1).

In 2150 exposure continues to increase compared to 2100. For lands located along the Channel and Atlantic coast, one may note a particularly strong enhancement of exposure for the scenario SSP5-8.5 low-confidence compared to the other scenarios. Such an enhancement is not found for Mediterranean Cdl lands, which is consistent with the exposure plateau for large SLR as revealed in Fig. 4.

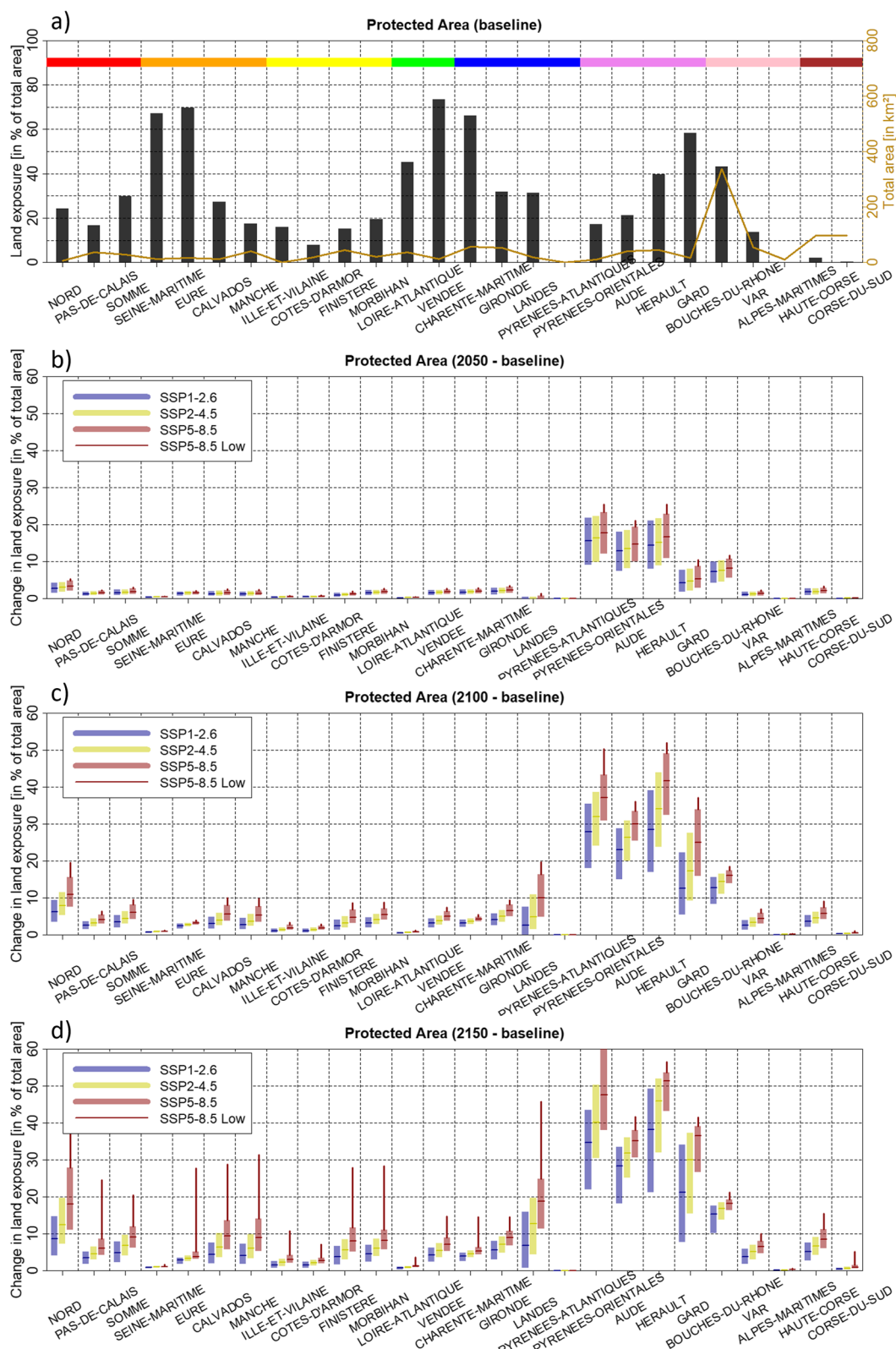


Fig. 5 a Baseline (i.e. contemporary with SLR of 0 m) of Cdl Protected Area low-lying land exposure (expressed in % of total land area per NUTS3 region) and **b, c, d** its projected change with respect to the baseline for 4 scenarios (SSP1-2.6, SSP2-4.5, SSP5-8.5 and SSP5-8.5 low confidence) and 3 timeslices (2050, 2100 and 2150). For reference, the total protected land area (in km²) for each NUTS3 region is shown on panel a (gold). Colored horizontal bars on top of panel a indicate NUTS1 region as shown in Fig. 1

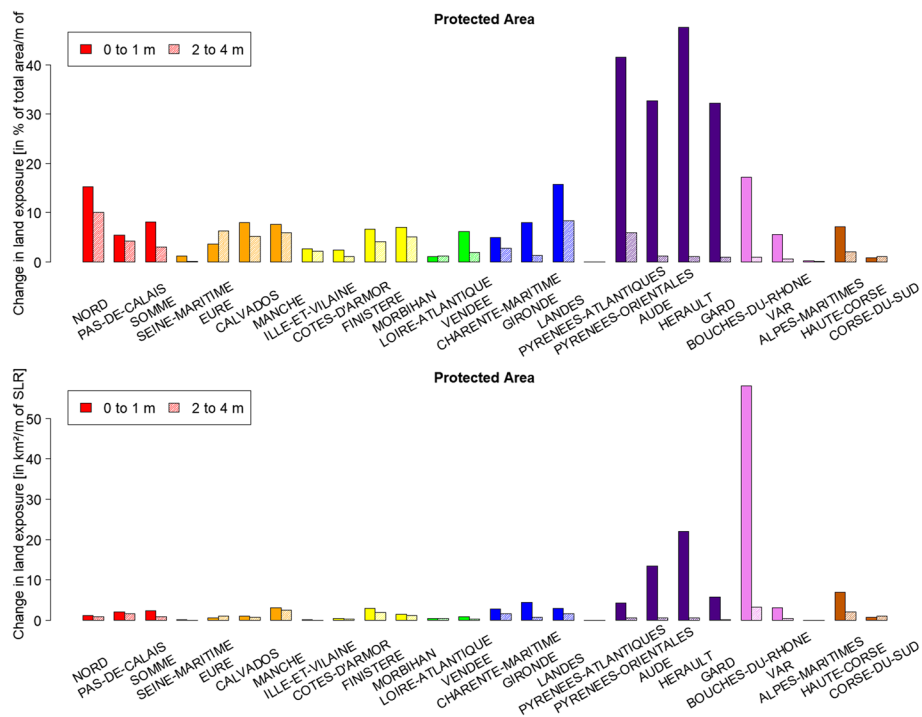


Fig. 6 Rate of change in Cdl low-lying land exposure with respect to SLR. Rates are shown in relative (in % of total land area/m of SLR) and absolute (in km²/m of SLR) values on the top and bottom panel, respectively. For each NUTS3 regions, rates are calculated for the SLR ranges 0–1 m (filled bars, left) and 2–4 m (hatched bars, right)

To further characterize how exposure evolves with SLR, we calculate exposure increase for two different SLR ranges: 0–1 m and 2–4 m. On the one hand, examining the SLR range 0–1 m allows assessing the sensitivity of exposure increase to SLR uncertainty over the 21st century. On the other hand, examining the SLR range 2–4 m allows assessing the sensitivity of exposure increase to large (and deep) SLR uncertainties that characterize longer terms (i.e. beyond 2100). Results are shown on Fig. 6 and read as follows: e.g. in the NUTS3 region “Somme”, the Protected land exposure increases by increments of 8% (of the total land area) per meter of SLR in the range 0–1 m, while it increases by increments of 3% per meter of SLR in the range 2–4 m. Apart from l’Eure, Cdl lands in all department show a larger exposure increase in the range 0–1 m than 2–4 m. As expected from the curves shown in Fig. 4, this effect is particularly pronounced for the Cdl lands along the Mediterranean coast. The analysis of rates in actual area extent values (i.e. km²/m instead of % of total area/m) reveals how large the rate of exposure increases in the department “Bouches-du-Rhones” in the range 0–1 m, with more than 50 km² per meter of SLR.

For the sake of conciseness, the regional analysis of land exposure change to SLR shown in the present

section was restricted to the Protected Area. The analysis was however also performed for the Authorized Perimeter and Strategy 2015–2050 land datasets (see Supplementary material B.2) and revealed very similar results.

3.3 Change in coastal land area by erosion

3.3.1 National scale

Projected loss of land at mainland scale due to shoreline retreat is reported on Table 4. Note that the loss is expressed in % of the total mainland France land of each type. In 2050, considering only the extrapolation of observed trends leads to a mean erosion of 0.6%, 0.6% and 0.4% within the uncertainty ranges 0.3–0.9%, 0.3–1.1% and 0.2–0.7% for the Protected Area, Authorized Perimeter and Strategy 2015–2050, respectively. Here the mean loss is obtained by averaging ShorelineMonitor rates of transects associated to each plot of land. The uncertainty range corresponds to the loss estimates when considering ShorelineMonitor rates plus or minus the 1-sigma uncertainty estimate. In 2100, following the same simple approach, we obtain a mean estimate of 1.3, 1.5 and 0.9% loss of land, for the three datasets respectively.

The impact of SLR on land loss is now investigated by adding the Bruun effect to the extrapolation of current trends. We tested the sensitivity of the results to three

different formulations of the Bruun rule by varying the beach slope parameter (see Section 2.3) and to three different climate change scenarios. Note that given the very large uncertainty on shoreline projection models (Toimil et al. 2020), we refrain from providing estimates beyond 2100 and for the SSP5-8.5 low-confidence scenario. In 2050, considering the steep beach slope (10%) Bruun formula leads to land loss estimates very close to the No SLR one (i.e. ~0.4–0.6% whatever the type of land or scenario). On the other hand, the formula that relies on the nearshore slopes of Athanasiou et al. (2019) double the No SLR estimates reaching an average estimate of ~1.3%, 1.6% and 0.9% for the Protected Area, Authorized Perimeter and Strategy 2015–2050, respectively. This first result stresses the potential large impact - but also the high uncertainty - related to the coastal erosion model when projecting future shoreline change. In 2050, we note no difference between the three scenarios. Conversely, in 2100, the difference in land loss projections is well pronounced between scenarios for both coastal erosion models that consider either a 1% slope or the nearshore slopes retrieved by Athanasiou et al. (2019). In the latter case, our estimates show for instance a land loss of 3.2% for the SSP1-2.6 against 4.1% for the SSP5-8.5 for the Protected Area dataset. This more than double the estimates of land loss that ignore the effect of SLR.

3.3.2 Regional scale

Land-loss projections in 2100 in NUTS3 regions for the Protected Area and different coastal erosion model and

scenarios are shown on Fig. 7. In general (and in relative terms: i.e. the land loss is computed relatively to the total land plot area of each department), the Protected Area (Fig. 7a) and Authorized Perimeter (Fig. 7b) appear more exposed to coastal erosion than the Strategy 2015–2050 (Fig. 7c) in consistency with results of Table 4. Figure 7 reveals however an important regional disparity in coastal erosion exposure.

Focusing first on the coastal erosion model that extrapolate recent observed trends (grey bars), the regions that appear the most threatened by erosion are namely located along the Atlantic and the west Mediterranean seaboard. These most affected regions appear to be common to the three land datasets. Conversely, the eastern Mediterranean, Corsica and few regions in the Northern France show no land loss projected over the 21st century. One should also notice that the uncertainty land plot loss can be very large as e.g. in Loire-Atlantique NUTS3 for Authorized Perimeter and Strategy 2015–2050 (Fig. 7b and c).

Uncertainties on land-loss projections are further amplified when adding SLR impact via the Bruun rule under different future climate scenarios. For the sake of readability, we did not repeat observed trends uncertainty bars on the land loss projections: i.e. we consider median SLR estimates only for each SSP scenario. Regions along the Atlantic coast appear particularly affected by the SLR-driven land loss, but also strongly sensitive to the Bruun formulation. As illustrated in the Vendée region for instance: for the Protected domain (Fig. 7a), our

Table 4 Projected loss of Cdl land in 2050 and 2100 considering scenarios SSP1-2.6, SSP2-4.5, SSP5-8.5. Four shoreline projection models are tested: either by extrapolating observed trends (i.e. Tx only) – in which case SLR has no effect, or by extrapolating observed trends and adding a Bruun model term with different formulations tested (see main text for details)

	2050				2100			
	No SLR	SSP1-2.6	SSP2-4.5	SSP5-8.5	No SLR	SSP1-2.6	SSP2-4.5	SSP5-8.5
Loss in Protected Area land area (in %)								
Tx only	0.6 [0.3–0.9]				1.3 [0.8–2.0]			
Tx + Bruun (10%)		0.6	0.6	0.6		1.4	1.4	1.4
Tx + Bruun (1%)		0.8	0.8	0.8		2.0	2.4	2.5
Tx + Bruun (Athanasiou et al. 2019)		1.2	1.3	1.3		3.2	3.8	4.1
Loss in Authorized perimeter land area (in %)								
Tx only	0.6 [0.3–1.1]				1.5 [0.7–2.8]			
Tx + Bruun (10%)		0.6	0.6	0.6		1.6	1.6	1.6
Tx + Bruun (1%)		0.9	1.0	1.0		2.5	2.9	3.1
Tx + Bruun (Athanasiou et al. 2019)		1.4	1.6	1.6		3.8	4.6	5.0
Loss in Strategy 2015–2050 land area (in %)								
Tx only	0.4 [0.2–0.7]				0.9 [0.4–1.7]			
Tx + Bruun (10%)		0.4	0.4	0.4		1.0	1.0	1.0
Tx + Bruun (1%)		0.6	0.6	0.6		1.4	1.7	1.8
Tx + Bruun (Athanasiou et al. 2019)		0.9	1.0	1.0		2.3	2.8	3.0

projections reveal near 7% land loss for the Tx erosion model, near 10% when adding the SLR contribution with a constant 1% slope and more than 12% when considering the variable nearshore slope. Along the Channel and Atlantic coast, the variable beach slopes are gentler than 1% leading to a larger projected coastal retreat and also to a higher sensitivity to SLR projections. This contrasts with the Mediterranean coast where beach slopes are steeper leading to similar land loss estimates when considering either a constant 1% slope or the variable nearshore slope datasets. Finally, one note that in some regions, the uncertainty linked to Tx is very larger and even overpass those linked to the SLR-driven land loss (e.g. in the Loire-Atlantique as shown on Fig. 7b and c).

4 Discussion

In this section, we compare our results to earlier assessments, highlight the significance of the results but also discuss the limitations of our approaches.

4.1 Low-lying land exposure

When Clus-Auby et al. (2006) performed the 1st assessment of the exposure of Cdl land to sea-level rise, the sea-level information that was available came from the Third Assessment Report of the IPCC. Hence, no regional projections were available, and the potential contribution of ice-sheets was considered small. At that time (early 2000's), Cdl owned already 590 km² (against 1,150 km² at present) and planned to acquire 1,160 km² more surface of lands by 2100. The results of this study were mainly driven by polderized lowlands areas, whether already owned or planned to be acquired by the Conservatoire du littoral. Without defense failure, Clus-Auby et al. (2006) estimated that the flooding would be limited to 3% of the land already owned and projected to be owned by the Conservatoire du littoral by 2100. Conversely, they estimated at 10% and 21%, the flooded area of land owned and projected to be owned, respectively, in case of defense failure. This latter approach is similar to the method we used in this study as coastal defenses are also ignored.

In our new assessment, we mapped and quantified the surface of low-lying Cdl lands located below high tide plus mean sea level relying on a recent high-resolution DEM. Under contemporary mean sea-level conditions,

we found that 30%, 33% and 42% of Protected Area, Authorized Perimeter and Strategy 2015–2050 lands are located below the high tide level, respectively. This appears already larger than the estimates of Clus-Auby et al. (2006) in 2100 even if they considered a 44 cm SLR offset. The comparison is not trivial though since in early 2000's, the Cdl owned only 50% of what we analyzed and planned for a 1,160 km² acquisition against a near 4,800 km² for the Strategy 2015–2050 dataset. Furthermore, some of the large NUTS1 region in Mediterranean seaboard were omitted by lack of information in the former assessment, in particular the Occitanie, which we found is highly exposed. Finally, one should note also that the method for assessing low-lying areas in the early 2000's assessment was relying on spatially sparse topographic estimates against a high-resolution gridded DEM in our case, which should again contribute to the difference between the two studies.

Our results projected a near 10% additional surface exposure by 2100 under high emission and high-end scenarios (SSP5-8.5 and SSP5-8.5 low confidence, respectively) and 2150 for moderate scenarios (SSP1-2.6 & SSP2-4.5) across all datasets. This means that even under strong mitigation policy, land area below high tides owned by the Cdl is projected to increase by at least 10% between 2100 and 2150. Although this exposure increase appears to be ineluctable, our results further suggest that if a high impact scenario is realized (i.e. in case of no climate change mitigation policy and given the high uncertainty on future ice-sheets contribution), one could not discard 20 to 30% additional surface exposure in ~100 years from now.

One significant finding of our assessment is that the increase in low-lying land exposure is not uniform regionally at the scale of mainland France and appears strongly amplified along the West Mediterranean coast. This corresponds to a region where sedimentation in lagoons and estuaries as well as longshore transport have generally extended the coastal flood plain since the stabilization of sea levels 6 000 years ago (Giaime et al. 2019; Vella et al. 2005). Today, bilateral meetings with the Cdl suggest that former lagoon areas can be perceived as the first areas at risks from high-tide flooding in southern France by some stakeholders. Yet, a further extension of flood prone areas would be limited by the small

(See figure on next page.)

Fig. 7 Projections of land loss through shoreline retreat (expressed in % of coastal land area per NUTS3 region) in 2100 for the **a** Protected area, **b** Authorized Perimeter and **c** Strategy 2015–2050 land datasets. The results from 3 shoreline projection models are shown: Tx only (the gray bar extent indicates the uncertainty), and 2 types of Bruun considering either a 1% constant beach slope (triangle) and varying nearshore slopes (dots). Colored symbols indicate that projections are performed with median SLR projection from SSP1-2.6 (blue), SSP2-4.5 (yellow) and SSP5-8.5 (red)

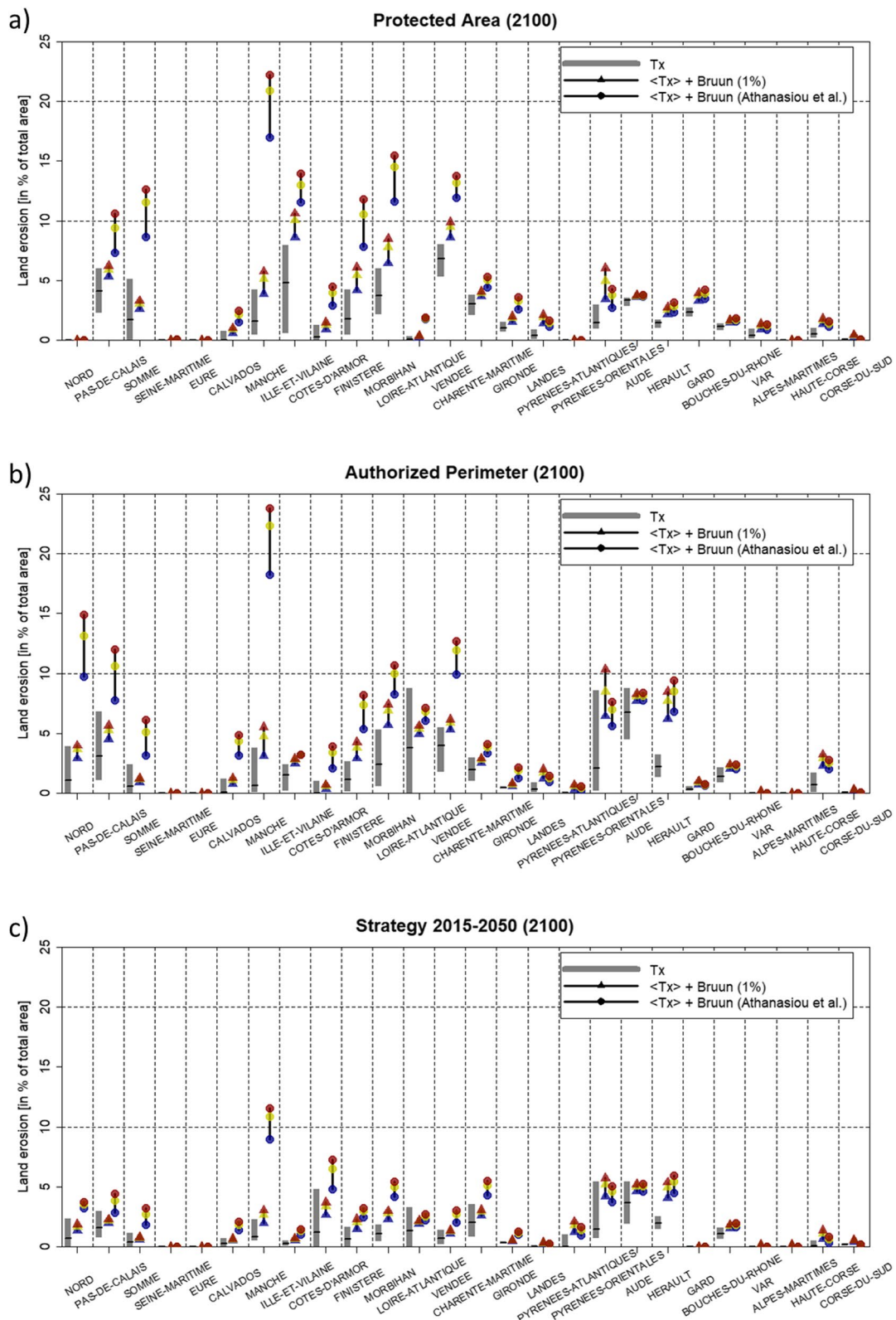


Fig. 7 (See legend on previous page.)

topographic features of areas that were never flooded by the sea during the Holocene, at least until SLR does not exceed several meters. Our results tend to confirm this perception. In this region (but also throughout the mainland coastal with a lesser amplitude though), our results suggest that the increase in low-lying land exposure is more sensitive to a SLR range 0–1 m than 2–4 m. In other words, near-future uncertainty on SLR have more impact on Cdl land exposure evolution than long-term deeply uncertain SLR scenarios. Although Cdl does not exclude acquiring land that could be exposed to permanent flooding in the future (see Section 3.1), the strongest sensitivity of Cdl land exposure to near future uncertainty on SLR shall be considered for their acquisition strategy, especially along the Mediterranean coast.

Finally, it is important to bear in mind that our approach assumes that defences are transparent, that water volumes are infinites and ignores water flow dynamics. As such, the analysis presented here corresponds to identify the maximum possible extent of the flood prone areas and allows a first quantitative assessment of Cdl low-lying areas exposed to SLR. We also examine how large could be the overestimate of low-lying areas as we did not account for hydraulic connectivity. To do so, we corrected the identified low-lying areas by considering only those that are hydraulically connected to the sea (excluding defences). We found that 95% of the low-lying area identified (over metropolitan France) from the static projection is hydraulically connected. Applying such a refinement has therefore a modest impact on our findings. Nevertheless, to avoid the strong assumptions mentioned above and aim at a finer analysis, hydrodynamical modelling would be relevant - although this could be done over rather restricted areas (Ramirez et al. 2016) - or storage-cell flooding modelling (Naulin et al. 2016).

4.2 Erosion

In their previous assessment, Clus-Auby et al. (2006) estimated a 1% land loss by 2100 through shoreline retreat for land already owned or projected to be owned. Their estimates relied on an analysis of namely aerials photographs from which they could derive shoreline trends. They then used these trends to extrapolate shoreline position in the future. At the end, the analysis covered almost 90% of the land owned by the Cdl or projected to be owned.

Using a similar trend extrapolation method but based on satellite-derived shoreline change, we found a 1% to 1.5% median land loss for the three Cdl datasets in 2100 for mainland France. This result appears to be consistent with the previous estimate of Clus-Auby et al. (2006) despite the fact that they included also soft cliffs and had half less plots of land to analyse. In our case, we focused

on the sandy coast and could therefore explore the impact of the SLR through various formulation of the Bruun rule. We found that adding the SLR effect could potentially multiply the land loss by two to three by 2100 depending on the model formulation or the SLR scenario. All these projections remain however highly uncertain as the observed rates may not be accurately detected, may not remain the same in the future, and as the adequacy of using the Bruun rule to estimate the erosional impacts of sea-level rise is disputed (Le Cozannet et al. 2019; Voudoukas et al. 2020; Cooper et al. 2020; D'Anna et al. 2021).

Comparing earlier and present assessments at regional scale, both studies found almost no land loss in the eastern Mediterranean compared to its western part. Clus-Auby et al. (2006) reported also rather large projected land loss in Northern France that our analysis suggests too. We note however some divergences over the Atlantic seaboard, where our results suggest a large land loss (even when examining absolute loss – not shown), which does not appear so important in Clus-Auby et al. (2006). Although some reasons for differences have already been mentioned above (larger dataset in our case, focus on sandy segment only), we also examined whether the differences could arise from the observational shoreline datasets used to retrieve shoreline trends.

First, we conducted a qualitative analysis down to the very local scale. In Clus-Auby et al. (2006), they provide details on erosion sites hotspot such as e.g. the “Dunes du Jaunay et de la Saussaie” in Vendée, Keruiny and the Audierne bay in Bretagne, numerous sites in Contentin but also some in west Mediterranean (e.g. La Grande Cosse). In the vast majority of locations, our method allowed confirming these hotspots of erosion. In few areas though, Les Garennes de Lornel (Northern France) and in the Dune du Pilat (Aquitaine) our estimates provide some indications that erosion could only be large assuming a significant contribution of the Bruun effect, whereas it was identified as clear eroding sectors in previous studies (Clus-Auby et al. 2006; Mallet et al. 2015). Those differences appear to be due to the modest erosion rates provided by the ShorelineMonitor results against those retrieved by Clus-Auby et al. (2006).

Second, we repeated our Cdl land loss estimates but based on shoreline change assessment over France provided by CEREMA (2017) instead of ShorelineMonitor rates. We found very similar results overall with a mean estimated loss of ~1% by 2100. The regional assessment indicates similar projections, with a close spatial distribution although of lesser magnitude (not shown). The detailed plot-by-plot comparison revealed an overall consistency, with a few noticeable differences though; e.g. Les Garennes de Lornel (Northern France) and in the Dune du Pilat (Aquitaine) indicates clear erosion projections when using the CEREMA shoreline change rates.

In conclusion, although our quantitative projections of land loss must be considered with caution as they are sensitive to uncertain coastal erosion processes but also sensitive to the historical observational data used to build these models, they remain relevant for first assessments of land loss at the regional scale for sandy beach segments. This relevance is supported by the fact that our estimates (i) are overall consistent with previous assessments and (ii) appear robust when using independent observational datasets to construct them. For detailed local projections and assessments, process-based shoreline evolution modelling (e.g. D'Anna et al. 2021) coupled with field analysis and expert judgments would help better constraining large uncertainties. Such detailed analysis are however not always feasible as they generally require extended observational data records for model calibration.

5 Conclusions and outlook

The French coastal conservation agency, the 'Conservatoire du littoral' (Cdl) has a strategic aim to own 25% of French coasts length and 3,200 km² of land by 2050. Historically these decisions took a static perspective and assumed the land existed in perpetuity. However, many areas are threatened by erosion and flooding due to sea-level rise and here we provide a first climate service to inform the land management and acquisition strategy. We quantify the exposure of the coastal land heritage owned or projected to be owned by the Conservatoire du littoral. Currently, 30% (and ~40%) of the Cdl lands owned (and projected to be owned) are located below the high tide level and this could reach ~40% (and ~50%) by 2100 or 2150 depending on greenhouse gases concentrations. At the high end, our results revealed that an expansion by 20 to 30% of additional surface exposure in ~100 years is unlikely, but cannot be discounted. More importantly, our findings suggest that increase in Cdl land exposure is more sensitive to near-future uncertainty on SLR and is particularly pronounced in the Mediterranean region. Concerning land loss by erosion, our result suggests that nearly 1% of land owned (or projected to be) by Cdl could be lost in 2100 if observed historical trends continue. Adding the SLR effect through the Bruun rule could lead to more than 3% land loss, but this strongly depends on the erosion model considered and the SLR trajectory.

Our study confirms previous findings that Cdl will need to consider land losses due to SLR and change its acquisition strategy to include more depth from the coast to create space for these dynamics with their land holdings. This is especially challenging on the Mediterranean French coast during the 21st century and for SLR below 1 m when the largest changes occur and obtaining additional land is most difficult. Cdl can adjust its land

acquisition strategy based on these results and regular updates via a climate service: e.g., using new land acquisition plans, updated sea-level projections, more advanced flood and erosion models and better cost and feasibility assessments of adaptation options. Although the decision considered here is specific to Cdl, the information needs in terms of flood and erosion projections for coastal conservation are standard and could benefit from a climate service for coastal adaptation in France or in Europe, and even more widely (e.g., USA, Australia, etc.).

In western Europe, coastal risk management has been dominated by engineered protection to date (Tol et al. 2008; Pranzini 2018). Today, the activities of Cdl are introducing softer management approaches and nature-based solutions through experiments such as removing coastal protection to leave space for water, ecosystems and sediments (Louisor et al. 2022) and community and stakeholder engagement (Gérard 2009; program Life ADAPTO: <https://www.lifeadapt.eu/>). These activities recognize that a sustained coastal adaptation strategy is more efficient when diverging interests are considered, and when trade-offs are proposed to accommodate coastal development, risk prevention, coastal adaptation and conservation (Cazals et al. 2018; Chouinard et al. 2015; Magnan 2014; Deboudt 2010). In this sense, the Cdl approach influences a much larger area than the 13% of French coastlines it currently owns. Its activities can contribute to the transition toward a more sustainable coast in France and more widely.

Supplementary Information

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Supplementary material 1.

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Authors' contributions

R.T., G.L.C., J.R., R.J.N. and A.P. designed the research. X.P., G.L.C. and A.P. organised bilateral meetings. R.T., R.G., C.N., A.L. and F.C. provided data and contributed to their analysis. A.P., J.R. and X.P. contributed to the interpretation of the results. R.T. and G.L.C. wrote the first version of the manuscript. All contributed to the paper writing, editing and revisions. G.L.C. and R.J.N. received the fundings.

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Availability of data and materials

Shoreline and topography datasets used in this study are publicly available and can be downloaded online at <https://geoservices.ign.fr/catalogue>. AR6 regional sea level projections dataset is available at <https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool>. EuroSION database is available at <https://www.eea.europa.eu/en/datahub/datahubitem-view/ba6d7fe6-c79f-48c7-b738-f78260730538>. The Shoreline Monitor dataset (<http://shoreline-monitor.deltares.nl>) and maps of low-lying areas (<https://sealevelrise.brgm.fr/slr/>) are accessible to the corresponding author upon reasonable request. The vector datasets of the Conservatoire du Littoral can be requested at sig@conservatoire-du-littoral.fr.

Declarations

Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

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References

- Athanasioiu P, van Dongeren A, Giardino A, Vousdoukas M, Gaytan-Aguilar S, Ranasinghe R (2019) Global distribution of nearshore slopes with implications for coastal retreat. *Earth Syst Sci Data* 11:1515–1529
- Bamber JL, Oppenheimer M, Kopp RE, Aspinall WP, Cooke RM (2019) Ice sheet contributions to future sea-level rise from structured expert judgment. *Proc Natl Acad Sci* 116:11195
- Bates PB, Dawson RJ, Hall JW, Horritt MS, Nicholls RJ, Wicks J, Hassan MAAM (2005) Simplified two-dimensional numerical modelling of coastal flooding and example applications. *Coast Eng* 52:793–810. <https://doi.org/10.1016/j.coastaleng.2005.06.001>
- Bazin P, Olivry D (2017) Le Conservatoire du littoral: un acteur face au changement climatique. *Sciences Eaux Territoires* 3:50–53
- Brown S, Nicholls RJ, Hanson S, Brundrit G, Dearing JA, Dickson ME, Gallop S, Gao S, Haigh ID, Hinkel J, Jiménez JA (2014) Shifting perspectives on coastal impacts and adaptation. *Nat Clim Chang* 4(9):752–755
- Bruun P (1962) Sea-level rise as a cause of shore erosion. *J Waterw Harb Div* 88:117–132
- Capar L, Hinkel J, Hammann A, Mätzler E, Le Bars D, Shareef A, Gussmann G, Thiéblemont R, Philippenko X, Rohmer J, Turner F, Nicholls R, Mottram R, Le Cozannet G (2020) D2.1 – Summary report on 1st global stakeholder workshop, December 2020. p 75
- Cazals C, Dachary-Bernard J, Lyser S (2018) L'acquisition foncière du conservatoire du littoral au service de patrimoines communs. *Sud-Ouest européen* [En ligne], 45 | 2018, mis en ligne le 11 avril 2019, consulté le 09 juin 2022. <https://doi.org/10.4000/soe.4223>. <http://journals.openedition.org/soe/4223>
- Cerema (2017) Spécification technique de l'indicateur national de l'érosion côtière, En ligne sur le site internet Géolittoral. <http://www.geolittoral.developpement-durable.gouv.fr/strategie-nationale-de-gestion-integree-du-trait-r434.html>
- Chouinard O, Weissenberger S, Lane D (2015) L'adaptation au changement climatique en zone côtière selon l'approche communautaire : études de cas de projets de recherche-action participative au Nouveau-Brunswick (Canada). *Vertigo - la revue électronique en sciences de l'environnement* [En ligne], Hors-série 23 | novembre 2015, mis en ligne le 25 novembre 2015, consulté le 10 novembre 2022. <https://doi.org/10.4000/vertigo.16642>. <http://journals.openedition.org/vertigo/16642>
- Clus-Auby C, Paskoff R, Verger F (2006) Le patrimoine foncier du Conservatoire du littoral et le changement climatique: scénarios d'évolution par érosion et submersion. *Ann Géogr* 648:115–132
- Conservatoire du littoral (2015) STRATÉGIE D'INTERVENTION DU CONSERVATOIRE • 2015 – 2050, p 30. Available <https://www.conservatoire-du-littoral.fr/97-strategie-d-intervention-2015-2050.htm>
- Cooley S, Schoeman D, Bopp L, Boyd P, Donner S, Ghebrehewet DY, et al (2022) Oceans and Coastal Ecosystems and Their Services. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner HO, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Lösschke S, Möller V, Okem A, Rama B (eds). Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 379–550. <https://doi.org/10.1017/9781009325844.005>
- Cooper JAG, Pilkey OH (2004) Sea-level rise and shoreline retreat: time to abandon the Bruun rule. *Glob Planet Change* 43(3–4):157–171
- Cooper JAG, Masselink G, Coco G, Short AD, Castelle B, Rogers K, Anthony E, Green AN, Kelley JT, Pilkey OH, Jackson DWT (2020) Sandy beaches can survive sea-level rise. *Nat Clim Chang* 10(11):993–995
- D'Anna M, Idier D, Castelle B, Vitousek S, Le Cozannet G (2021) Reinterpreting the Bruun rule in the context of equilibrium shoreline models. *J Mar Sci Eng* 9(9):974
- Deboudt P (2010) Vers la mise en œuvre d'une action collective pour gérer les risques naturels littoraux en France métropolitaine. *Cybergeo, Espace, Société, Territoire*, document 491. <https://doi.org/10.4000/cybergeo.22964>. <http://journals.openedition.org/cybergeo/22964>
- DeConto RM, Pollard D, Alley RB et al (2021) The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature* 593:83–89. <https://doi.org/10.1038/s41586-021-03427-0>
- Doze E (2015), Le changement climatique et les propriétés du Conservatoire du littoral, *Vertigo - la revue électronique en sciences de l'environnement*, Hors-série 21, consulté le 10 novembre 2022. <https://doi.org/10.4000/vertigo.15778>. <http://journals.openedition.org/vertigo/15778>
- Durand G, van den Broeke MR, Le Cozannet G, Edwards TL, Holland PR, Jourdain NC, Marzeion B, Mottram R, Nicholls RJ, Pattyn F, Paul F, Slangen ABA, Winkelmann R, Burgard C, van Calcar CJ, Barré J-B, Bataille A, Chapuis A (2022) Sea-level rise: from global perspectives to local services. *Front Mar Sci* 8:709595. <https://doi.org/10.3389/fmars.2021.709595>
- Edward TL, Nowicki S, Marzeion B et al (2021) Projected land ice contributions to twenty-first-century sea level rise. *Nature* 593:74–82. <https://doi.org/10.1038/s41586-021-03302-y>
- Fox-Kemper B, Hewitt HT, Xiao C, Aðalgeirsdóttir G, Drijfhout SS, Edwards TL, et al (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, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362. <https://doi.org/10.1017/9781009157896.011>
- Garner GG, Hermans T, Kopp RE, Slangen ABA, Edwards TL, Levermann A, Nowicki S, Palmer MD, Smith C, Fox-Kemper B, Hewitt HT, Xiao C, Aðalgeirsdóttir G, Drijfhout SS, Edwards TL, Gollledge NR, Hemer M, Krinner G, Mix A, Notz D, Nurhati IS, Ruiz L, Sallée J-B, Yu Y, Hua L, Palmer T, Pearson B (2021) IPCC AR6 Sea-Level Rise Projections. Version 20210809. PO.DAAC, CA, USA. Dataset accessed [YYYY-MM-DD] at <https://podaac.jpl.nasa.gov/announcements/2021-08-09-Sea-level-projections-from-the-IPCC-6th-Assessment-Report>
- Gérard Y (2009) Une gouvernance environnementale selon l'état ? Le conservatoire du littoral entre intérêt général et principe de proximité. *Vertigo* 9:1. <https://doi.org/10.4000/vertigo.8551>. <http://journals.openedition.org/vertigo/8551>
- Giaime M, Marriner N, Morhange C (2019) Evolution of ancient harbours in deltaic contexts: a geoarchaeological typology. *Earth Sci Rev* 191:141–167
- Gregory JM, Griffies SM, Hughes CW, Lowe JA, Church JA, Fukimori I, Gomez N, Kopp RE, Landerer F, Le Cozannet G, Ponte RM, Stammer D, Tamisiea ME, van de Wal RSW (2019) Concepts and terminology for sea level: mean, variability and change, both local and global. *Surv Geophys* 40:1251–1289. <https://doi.org/10.1007/s10712-019-09525-z>
- Hinkel J, Lincke D, Vafeidis AT, Perrette M, Nicholls RJ, Tol RSJ, Marzeion B, Fettweis X, Ionescu C, Levermann A (2014) Coastal flood damage and adaptation costs under 21st century sea-level rise. *P Natl Acad Sci USA* 111:3292–3297. <https://doi.org/10.1073/pnas.1222469111>

- Hinkel J et al (2019) Meeting user needs for sea level rise information: a decision analysis perspective. *Earth's Future* 7:320–337. <https://doi.org/10.1029/2018EF001071>
- IPBES (2019) Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In: Brondizio ES, Settele J, Díaz S, Ngo HT (eds). IPBES secretariat, Bonn, p 1148. <https://doi.org/10.5281/zenodo.3831673>
- Kopp RE, Gilmore EA, Little CM, Lorenzo-Trueba J, Ramenzoni VC, Sweet WV (2019) Usable science for managing the risks of sea-level rise. *Earth's Future* 7:1235–1269. <https://doi.org/10.1029/2018ef001145>
- Lawrence J, Stephens S, Blackett P, Bell RG, Priestley R (2021) Climate services transformed: decision-making practice for the coast in a changing climate. *Front Mar Sci* 8:703902. <https://doi.org/10.3389/fmars.2021.703902>
- Le Cozannet G, Nicholls RJ, Hinkel J, Sweet WV, McInnes KL, Van de Wal RSW, Slangen ABA, Lowe JA, White KD (2017) Sea level change and coastal climate services: the way forward. *J Mar Sci Eng* 5:49. <https://doi.org/10.3390/jmse5040049>
- Le Cozannet G, Bulteau T, Castello B, Ranasinghe R, Wöppelmann G, Rohmer J, Bernon N, Idier D, Louisor J, Salas-y-Méllia D (2019) Quantifying uncertainties of sandy shoreline change projections as sea level rises. *Sci Rep* 9(1):42. <https://doi.org/10.1038/s41598-018-37017-4>
- Lichter M, Vafeidis AT, Nicholls RJ, Kaiser G (2011) Exploring data-related uncertainties in analyses of land area and population in the “Low-Elevation Coastal Zone” (LECZ). *J Coastal Res* 27(4):757–768
- Louisor J, Brivois O, Mouillon P, Maspataud A, Belz P, Laloue J-M (2022) Coastal flood modeling to explore adaptive coastal management scenarios and land-use changes under sea level rise. *Front Mar Sci* 9:710086. <https://doi.org/10.3389/fmars.2022.710086>
- Luijendijk A, Hagenaars G, Ranasinghe R, Baart F, Donchyts G, Aarninkhof S (2018) The state of the world's beaches. *Sci Rep* 8:6641
- Magnan A (2014) Avoiding maladaptation to climate change: towards guiding principles. *SAPIENS* (7.1). Vol.7/n°1.
- Mallet C, Millescamps B, Hoareau A (2015) Estimation de l'évolution du trait de côte aux horizons 2020-2040-2100 de la Dune du Pilat au Banc du Pineau et de Capbreton à l'embouchure de l'Adour. Rapport provisoire. BRGM/RP-64723-FR, 51 p., 30 fig., 6 tab., 4 ann
- Meur-Férec C (1997) A comparative review of coastal conservation policies in France, and England and Wales. *J Coast Conserv* 3(1):121–132
- Naulin JP, Moncoulon D, Le Roy S, Pedreros R, Idier D, Oliveros C (2016) Estimation of insurance-related losses resulting from coastal flooding in France. *Nat Hazards Earth Syst Sci* 16:195–207. <https://doi.org/10.5194/nhess-16-195-2016>
- Neumann B, Vafeidis AT, Zimmermann J, Nicholls RJ (2015) Future coastal population growth and exposure to sea-level rise and coastal flooding – a global assessment. *PLoS One* 10(3):e0118571. <https://doi.org/10.1371/journal.pone.0118571>
- Poulter B, Halpin PN (2008) Raster modelling of coastal flooding from sea-level rise. *Int J Geogr Inf Sci* 22:167–182. <https://doi.org/10.1080/13658810701371858>
- Pranzini E (2018) Coastal erosion and shore protection: a brief historical analysis. *J Coast Conserv* 22(5):827–830. <https://doi.org/10.1007/s11852-017-0521-9>
- Ramirez JA, Lichter M, Coulthard TJ et al (2016) Hyper-resolution mapping of regional storm surge and tide flooding: comparison of static and dynamic models. *Nat Hazards* 82:571–590. <https://doi.org/10.1007/s11069-016-2198-z>
- Riahi K, van Vuuren DP, Kriegler E, Edmonds J, O'Neill B, Fujimori S, Bauer N, Calvin K, Dellink R, Fricko O, Lutz W, Popp A, Crespo Cuaremas J, Leimbach M, Kram T, Rao S, Emmerling J, Hasegawa T, Havlik P, Humpenöder F, Aleluia Da Silva L, Smith SJ, Stehfest E, Bosetti V, Eom J, Germon D, Masui T, Rogelj J, Streffer J, Drouet L, Krey V, Luderer G, Harmsen M, Takahashi K, Wise M, Baumstark L, Doelman J, Kainuma M, Klimont Z, Marangoni G, Moss R, Lotze-Campen H, Obersteiner M, Tabeau A, Tavoni M (2017) The Shared Socio-Economic Pathways and their energy, land use and greenhouse gas emissions implications: an overview. *Glob Environ Change* 42:153–168. <https://doi.org/10.1016/j.gloenvcha.2016.05.009>
- Rohmer J, Lincke D, Hinkel J, Le Cozannet G, Lambert E, Vafeidis AT (2021) Unravelling the importance of uncertainties in global-scale coastal flood risk assessments under sea level rise. *Water* 13:774. <https://doi.org/10.3390/w13060774>
- Shom - Institut Géographique National (IGN) (2010). Trait de côte Histolitt Métropole et Corse V2. Available at https://services.data.shom.fr/geonetwork/srv/api/records/BDML_TCH_METROV2.xml
- Simm J, Gouldby B, Lumbroso D, Matthewson T (2021) Effective coastal climate services—an end-user perspective for resilient infrastructure. *Front Mar Sci* 8:706048. <https://doi.org/10.3389/fmars.2021.706048>
- Slangen ABA, Carson M, Katsman CA, van de Wal RSW, Kohl A, Vermeersen LLA, Stammer D (2014) Projecting twenty-first century regional sea-level changes. *Clim Change* 124:317–332. <https://doi.org/10.1007/s10584-014-1080-9>
- Tellez-Arenas A, Quique R, Boulahya F, Le Cozannet G, Paris F, Le Roy S, Dupros F, Robida F (2018) Scalable interactive platform for geographic evaluation of sea-level rise impact combining high-performance computing and WebGIS Client. In: Serrao-Neumann S, Coudrain A, Coulter L (eds) Communicating climate change information for decision-making. Springer, Cham, pp 163–175
- Thiéblemont R, Le Cozannet G, Toimil A, Meyssignac B, Losada IJ (2019) Likely and high-end impacts of regional sea-level rise on the shoreline change of European sandy coasts under a high greenhouse gas emissions Scenario. *Water* 11:2607. <https://doi.org/10.3390/w1122607>
- Thiéblemont R, Le Cozannet G, Rohmer J, Toimil A, Álvarez-Cuesta M, Losada IJ (2021) Deep uncertainties in shoreline change projections: an extra-probabilistic approach applied to sandy beaches. *Nat Hazards Earth Syst Sci* 21:2257–2276. <https://doi.org/10.5194/nhess-21-2257-2021>
- Toimil A, Camus P, Losada IJ, Le Cozannet G, Nicholls RJ, Idier D, Maspataud A (2020) Climate change-driven coastal erosion modelling in temperate sandy beaches: methods and uncertainty treatment. *Earth Sci Rev* 202:103110
- Tol RSJ, Klein RJT, Nicholls RJ (2008) Towards successful adaptation to sea-level rise along Europe's coasts. *J Coastal Res*. <https://doi.org/10.2112/07A-0016.1>
- Vafeidis AT, Schuerch M, Wolff C, Spencer T, Merken JL, Hinkel J, Lincke D, Brown S, Nicholls RJ (2019) Water-level attenuation in global-scale assessments of exposure to coastal flooding: a sensitivity analysis. *Nat Hazards Earth Syst Sci* 19:973–984. <https://doi.org/10.5194/nhess-19-973-2019>
- Vella C, Fleury TJ, Raccasi G, Provansal M, Sabatier F, Bourcier M (2005) Evolution of the Rhône delta plain in the Holocene. *Mar Geol* 222:235–265
- Vitousek S, Barnard PL, Limber P (2017) Can beaches survive climate change? *J Geophys Res Earth Surf* 122(4):1060–1067
- Vousdoukas MI, Mentaschi L, Voukouvalas E, Verlaan M, Feyen L (2017) Extreme sea levels on the rise along Europe's coasts. *Earth's Future* 5(3):304–323
- Vousdoukas MI, Ranasinghe R, Mentaschi L, Plomaritis TA, Athanasiou P, Luijendijk A, Feyen L (2020) Sandy coastlines under threat of erosion. *Nat Clim Chang* 10(3):260–263