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Benefits of adapting to sea level rise: the importance of ecosystem services in the French Mediterranean sandy coastline

Cécile Hérivaux, BRGM, Univ Montpellier, 1039 rue de Pinville, 34000 Montpellier, France, c.herivaux@brgm.fr
Hélène Rey-Valette, LAMETA, Univ Montpellier, helene.rey-valette@univ-montp1.fr
Bénédicte Rulleau, IRSTEA, benedicte.rulleau@irstea.fr
Anne-Laurence Agenais, BRGM, Univ Montpellier, ESPELIA, anne-laurence.agenais@espelia.fr
Marianne Grisel, ARTELIA Water & Environment, Marianne.GRISEL@arteliagroup.com
Laure Kuhfuss, LAMETA, Univ Montpellier, SGSD, Univ of St Andrews, lk38@st-andrews.ac.uk
Laure Maton, BRGM, Univ Montpellier, l.maton@montpellier3m.fr
Charlotte Vinchon, BRGM, c.vinchon@brgm.fr

Abstract

This article proposes an innovative approach to assess the benefits of adapting to sea level rise (SLR) in a coastal area on a regional scale. The valuation framework integrates coastal ecosystem services, together with urban and agricultural assets. We simulate the impacts of a progressive 1 m rise in sea level in the 21st century and an extreme flooding event in 2100 for four contrasted adaptation scenarios (Denial, "*Laissez-faire*", Protection and Retreat). The assessment involves coupling the results of hazard-modelling approaches with different economic valuation methods, including direct damage functions and methods used in environmental economics. The framework is applied to the French Mediterranean sandy coastline. SLR will result in major land-use changes at the 2100 time horizon: relocation or densification of urban areas, loss of agricultural land, increase in lagoon areas and modification of wetlands (losses, migration or extension of ecosystems). Total benefits of public adaptation options planned in advance could reach €31.2 billion for the period 2010-2100, i.e. €69,000 per inhabitant (in the study area) in 2010 or €135 million/km of coastline. Our results highlight the importance of (i) raising awareness to ensure that public services and coastal managers can anticipate the consequences of SLR and (ii) incorporating coastal ecosystems into the assessment of the adaptation options. Our findings could provide a basis for participatory foresight approaches to build coastline adaptation pathways.

Keywords: sea level rise; ecosystem services; adaptation options; climate change; economic valuation

1. INTRODUCTION

Coastal systems and low-lying areas will be increasingly at risk from flooding in the 21st century as a result of a progressive sea level rise (SLR) and extreme flooding (Wong et al. 2014). Assessing the vulnerability of coastal zones to SLR has become an increasingly important field of research since the 1980s. Yohe (1990) and Titus (1990) were among the first to analyse the consequences of this phenomenon. They investigated the economic vulnerability of coastal areas to a 0.5 to 2 m SLR at the scale of the United States.

Since then, several types of approaches have been developed at a local and global level. At a local scale, researchers use process-based models and elevation-based GIS analyses to determine the economic impacts of SLR. They focus primarily on the impacts of SLR with regard to the population, infrastructure and buildings in an urban context (Hallegatte et al. 2011; Lichter and Felsenstein 2012; Kebede and Nicholls 2012; Fletcher et al. 2016). Global scale assessments have been conducted using integrated assessment models, such as the DIVA model (Hinkel et al. 2013) or the FUND model (Anthoff et al. 2010). So far, the regional (sub-national) scale has been overlooked. However, on a regional scale, decision-support tools are required to anticipate SLR and ensure that those responsible for land-use and natural resource management can plan adaptation policies.

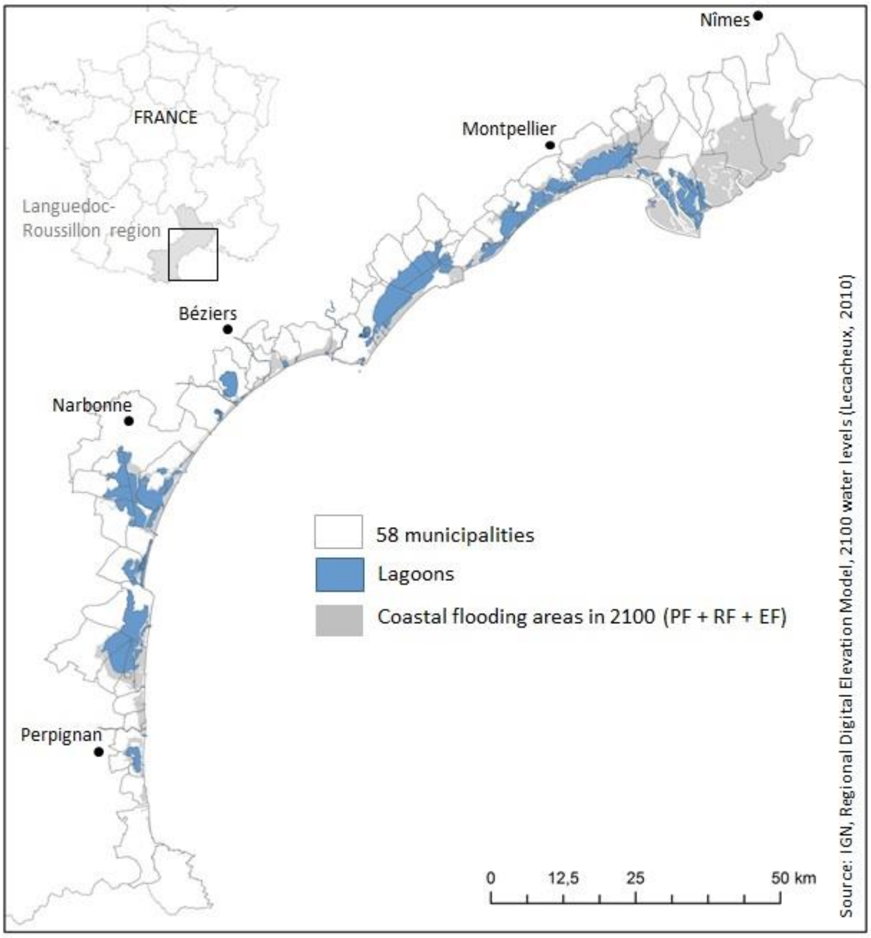
SLR could impact the coastal area in several ways (Wong et al. 2014). In urban and agricultural areas, SLR may force people to migrate. It may cause loss or damage to crops, land, housing and buildings. In addition, SLR may have an impact on ecosystems, such as beach loss, lagoon extension, wetland migration and groundwater salinisation. The economic impact of SLR generally focuses on urban and agricultural areas. Little research has been done to assess the economic impacts of SLR on ecosystems. In general, existing studies focus on characterising the physical impacts of SLR with regard to a particular coastal ecosystem (see for instance: Monioudi et al. 2014 for beaches; Craft et al. 2009 for wetlands; Li et al. 2015 for mangroves), without considering the associated economic impacts. Failure to take account of the economic impact means that the latter cannot be put into perspective with other expected impacts. However, coastal ecosystems are essential components of coastal areas. By providing a variety of ecosystem services, they make a significant contribution to the welfare of residents, tourists and day trippers (MEA 2005). The loss or transformation of coastal ecosystems resulting from SLR could affect ecosystem services and, therefore, have an impact on human well-being. As underlined by Lin et al. (2014) "*any assessment that incorporates only goods with market proxies (such as property, human health, or economic production) risks seriously underestimating both the costs and the benefits of the adaptation options*". Thus, analysing the impacts of SLR on coastal ecosystems and the services they provide could be beneficial for coastal managers when it comes to raising awareness about the need to anticipate SLR and choose the best strategy for adaptation. Overall, the IPCC (Wong et al. 2014) claims that the economics of coastal adaptation are under-researched and that more comprehensive assessments are needed for the valuation of coastal ecosystem services. In this perspective, the article aims to provide a comprehensive assessment of the benefits of adapting to SLR at a regional scale. It proposes an innovative approach that integrates coastal ecosystem services, as well as urban and agricultural assets, within the valuation framework. We simulate the impacts of a gradual 1 m rise in sea level over the 21st century and an extreme flooding event in 2100 for four contrasted adaptation scenarios (Denial, "*Laissez-faire*", Protection and Retreat). We study the gradual impacts of loss of land and land-use changes, and other impacts due to SLR such as saltwater intrusion. The assessment involves coupling the results of hazard-modelling approaches with various economic valuation methods, including direct damage functions and valuation methods used in environmental economics. Our objective is to estimate the potential benefits of adapting to SLR to help decision makers discussing the possible consequences of the different adaptation options.

2. SLR AND ADAPTATION OPTIONS FOR THE FRENCH MEDITERRANEAN SANDY COASTLINE

2.1 The French Mediterranean sandy coastline

The scope of our research covers the Languedoc-Roussillon coastline, which extends over 231 km and mainly consists of a low-lying sandy coast (Figure 1). Population growth in the Languedoc-Roussillon administrative region is among the highest in France, with an annual increase of 33,000 inhabitants since 1999. Over and above the major cities (such as Montpellier, Nimes and Perpignan), population density is particularly high along the coast. Urban development along the coastline began in the 1960s, with the creation of tourist sea resorts. Coastal risks were largely overlooked. The region is one of the most popular tourist destinations in France. In 2014, 8.5 million tourists visited the region (CCI Languedoc-Roussillon), generating €7 billion from tourism, i.e. 13% of regional GDP (INSEE).

Currently, sandy beaches make up 70% of the coastline and alternate with built-up areas. Regional Mediterranean wetlands represent 17% of all French wetlands of international importance (CGDD 2010). Almost all of them are community interest habitats under the European Habitats Directive and belong to the Natura 2000 network. Six aquifers located in the coastal area are of regional importance, representing 100 million cubic metres of groundwater, which provides 32% of the regional drinking-water supply (AERMC). Agricultural land accounts for 42% of the study area (SIG-LR[1]) and is dominated by vineyards, followed by cereals, fruit and vegetables, grassland and rice.



Source: IGN, Regional Digital Elevation Model, 2100 water levels (Lecacheux, 2010)

Fig. 1 Study area

The coast is already subject to marine flooding, especially during the winter season. For instance, the winter storm of 1982 generated a 1.7 m storm surge in the municipality of Palavas-les-Flots, where the mean ground elevation is 0.3 m. The storm caused 15 casualties and damaged buildings and marinas. At the regional scale, the direct costs of damage to non-insured assets alone amounted to €18 million. Sandy beaches are also subject to erosion. Since the 1960s, robust coastal protection works (mostly groynes and breakwaters) have gradually been built along the sandy shoreline, particularly in urban and tourist areas. In 2010, 285 coastal protection works were recorded in the study area (Vanroye and Auffret 2010). Over the last 20 years, strategies for coastal protection have evolved from these "hard" engineering techniques to much "softer" approaches (beach nourishment). According to Vanroye and Auffret (2010), the 1948-2010 cumulative cost for fighting erosion amounts to €117 million.

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[1] http://www.siglr.org/

2.2 Impacts of SLR on coastal flooding areas

Climate change and a gradual SLR are expected to increase these expenses due to marine flooding in the coming decades. Adapting the IPCC (Wong et al. 2014) hypotheses to the case of the Languedoc-Roussillon gives a worst-case scenario, with a 1 m rise in sea level by 2100 and greater storm impact due to higher water levels. Figure 2 presents the expected change in water levels for three return periods in relation to coastal flooding (Lecacheux et al. 2010): (i) permanent flooding (PF) (area flooded 100% of the time), which corresponds to the mean meteorological conditions and the lowest astronomical tides; (ii) recurrent flooding (RF) (area flooded at least twice a year), which corresponds to the mean annual meteorological conditions and the highest astronomical tides; and (iii) extreme flooding (EF), which corresponds to a 100-year return period for a winter storm surge (the winter 1982 storm is used as the reference).

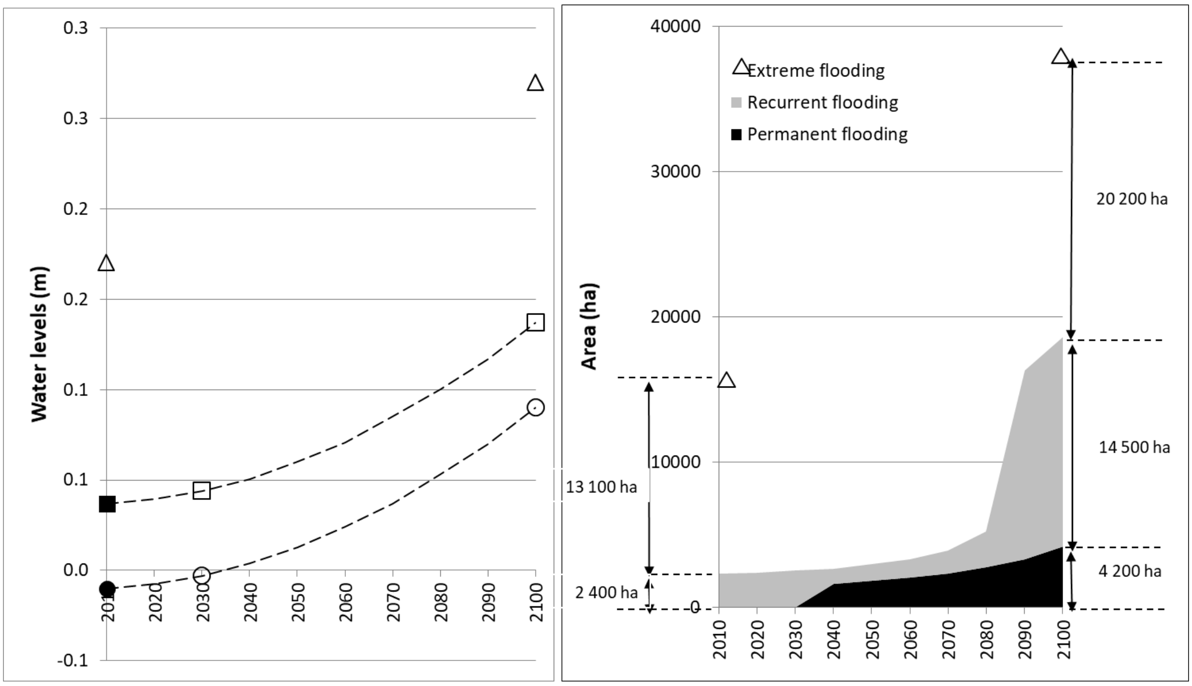

Fig. 2 Evolution of (a) water levels and (b) coastal flooding area resulting from PF, RF and EF over time. Legend (a): observed (●) and simulated (○) permanent water level; observed (■) and simulated (□) recurrent water level; average simulated extreme water level (Δ); --- extrapolation of permanent and recurrent water levels over time (polynomial trend curve).

Crossing simulated water levels with the regional Digital Elevation Model (Lecacheux et al., 2010) shows that the coastal areas affected by SLR will increase slowly until 2080. From then on, the rate of increase is expected to accelerate because of the topography of the study area. The coastal areas affected by PF or RF are likely to increase by a factor of 3.5 between 2080 and 2100 (Figure 2). In 2100, 58 coastal municipalities (Figure 1) may be exposed to coastal flooding, with 18,500 ha flooded by PF or RF (9% of total area), of which 4,200 ha of land will be permanently flooded. Results also show that in 2100, EF is likely to affect a larger area (20,200 ha, an area 55% greater). This is quite distinct from the area affected by EF in 2010. Overall, almost 39,000 ha may be exposed to coastal flooding in 2100 compared to 15,000 ha in a situation without SLR.

2.3 Potential adaptation options

As a response to these threats, several adaptation options may be envisaged. The IPCC classification of coastal adaptation strategies consisting of retreat, accommodation and protection (Nicholls et al. 2007) is now widely used and applied in both developed and developing countries (Wong et al., 2014). We adapted this classification to integrate the concepts of anticipatory *versus* reactive, and planned (collective state-regulated) versus individual decision-making (Tompkins, 2008). Options based on individual decision-making come from Yohe et al. (1996) and Michael (2007). On this basis, we frame four contrasted management options:

- Option 1: “Denial” assumes that there is neither anticipation nor adaptation. It is typically characterised by individual reactive decision-making, which corresponds to an option that could also be named “inaction”, “worst case” or “no foresight” (Yohe et al. 1996; Michael 2007). In this case, citizens are unaware of the SLR threat because only partial knowledge or information is available. Thus, there is no warning and consequently no structural depreciation of properties.
- Option 2: “*Laissez-faire*” assumes that there is no collective state-regulated strategy of adaptation. It relies on individual anticipatory decision-making. The threat of SLR is relatively well-known, which means citizens can anticipate. Greater awareness of the threat of SLR is expected to trigger a gradual depreciation in the economic value of housing, businesses and other structures exposed to flooding (Yohe et al.. 1996).
- Option 3: “Protection” assumes planned anticipatory decision-making. It consists of protecting the entire coastline from PF and RF, by implementing a combination of hard engineering techniques (dikes, seawalls) and softer approaches (beach nourishment, dune restoration).
- Option 4: “Retreat” assumes a strategic, anticipatory and planned relocation of structures and activities beyond the area exposed to flooding.

In the last decades, the Protection option was implemented to preserve the Languedoc-Roussillon coastline. Since the adoption in 2012 of the French national strategy of integrated coastline management, the Retreat option is now promoted by the French Environment Ministry (MEDDTL 2002). The progressivity of SLR, the slow increase in areas expected to be flooded by 2080, and the steady decline in public resources (both financial and human) suggest that public authorities will do little in terms of adaptation to the threat of SLR in the near future (Denial and

"*Laissez-faire*" options). These options are likely to have a severe impact on future generations over the period 2080-2100. It takes time to implement adaptation strategies for SLR. Raising the awareness of citizens and elected representatives about the benefits of such different options may be helpful to initiate the design of adaptation pathways at the regional level.

3. METHOD

3.1 Overview of the valuation framework

We propose a valuation framework to assess the benefits of these four contrasted management options. The framework is organised into five main steps (Figure 3):

- Step 1 consists of building narrative scenarios for the coastal area at the 2100 horizon. We consider that the changes affecting the coastal area will predominantly be driven by (i) the evolution in water levels, (ii) the option chosen to adapt to SLR and (iii) population growth (assumed to remain constant in the study area, with a linear increase based on INSEE 1988-2006 statistics). Narrative scenarios were built during a 2-day project meeting[2] between scientific researchers from a broad range of disciplines (sedimentology, geography, sociology, economics and agronomy). As a result, four adaptation scenarios (one for each of the adaptation options discussed in 2.3), describe the plausible evolutions likely to affect the coastal area. The scenarios make assumptions about the associated land-use changes (Online Resource 2).
- Step 2 provides quantitative estimates of land-use changes for each scenario in the 58 municipalities exposed to coastal flooding. The following categories of land use are considered: urban, agricultural, forest and semi-natural, lagoons, wetlands, beaches and dunes. The 2006 regional land cover GIS database SIG-LR[3], completed by Natura 2000 database, provides the basis for the analysis. Curves depicting the evolution of the coastal flooding area due to PF and RF (Figure 2) are used to quantify the areas gained or lost by each land-use category over time.
- Step 3 consists of understanding the impacts of PF and RF during the 2010-2100 period for each land-use category and adaptation scenario. The impacts are described in terms of (i) damage to assets located in urban and agricultural areas and (ii) changes in the services provided by coastal ecosystems. First, they are characterised in physical terms before being assessed in economic terms. We assume that the number of assets

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[2] Activity conducted as part of the multidisciplinary MISEEVA research project, funded by the French National Research Agency

[3] http://www.siglr.org/

and the importance of ecosystem services are proportional to the corresponding land-use category. In other words, the impacts can be linked to the area gained or lost due to PF and RF over time.

- Step 4 involves the characterisation of the physical impacts and an economic valuation of an EF event that occurs in 2100. The impact assessment of an EF event in 2100 is based on the EF area with the 2100 projected land use for each scenario and provides a comparison with a situation with no SLR.
- Step 5 assesses the benefits of adapting to SLR. It compares the impacts of progressive SLR and an EF event (in 2100) in the Denial scenario with the three other adaptation scenarios.

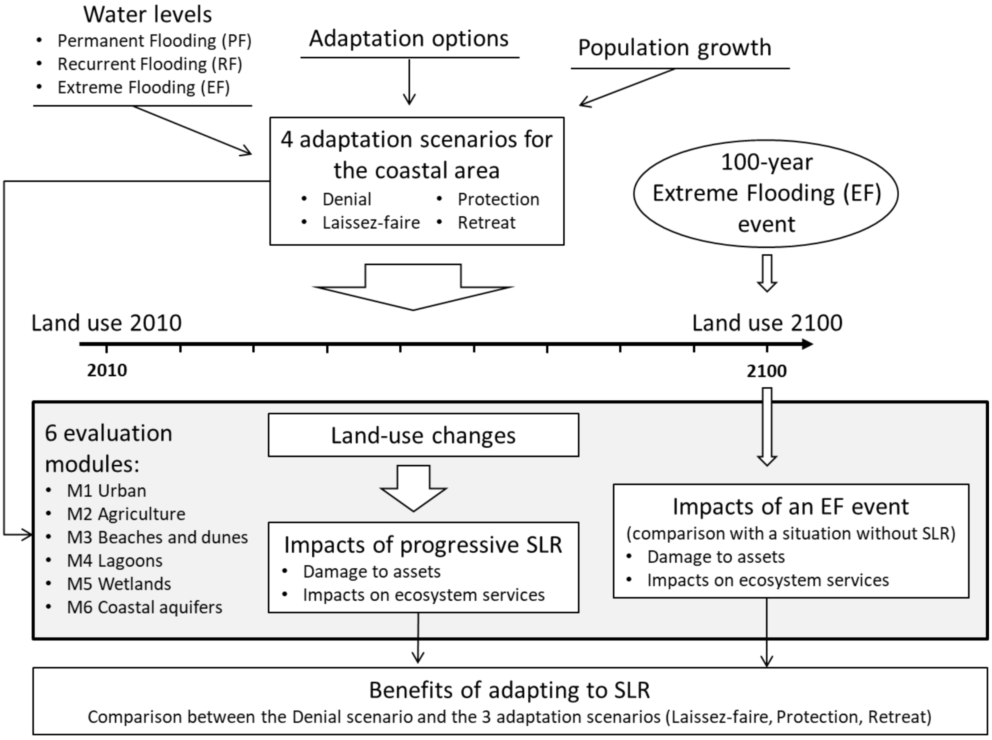

Fig. 3 Diagram describing the valuation framework

Steps 2 to 4 are implemented using six separate evaluation modules (M1 to M6), one for each land-use category and one for coastal aquifers. Each module applies several methodological approaches (Table 1), depending on the type of asset and service. The following sections (3.2 to 3.7) focus on each evaluation module. Further details on materials and methods can be found in Sogreah (2011) for urban areas, Agenais (2010) for agriculture, Rulleau and Rey-Valette (2013) and Rulleau et al. (2015) for beaches and dunes, and Kuhfuss et al. (2016) for lagoons and wetlands. Details on the valuation functions are provided in Online Resource 1.

3.2 Urban (M1)

In urban areas, M1 considers that PF and RF will force people to migrate and will cause loss or damage to land, housing and businesses if no protective measures are implemented. The analysis excludes the impacts on infrastructure (roads, bridges, railways). It is assumed that progressively flooded urban areas (in the Denial, "*Laissez-faire*" and Retreat options) are relocated beyond the EF zone, onto predominantly agricultural land in the same municipality, as far as possible. The economic cost of urban land loss is assessed at its opportunity cost, i.e. the value of interior agricultural land (3.3) and not the value of urban coastland (Yohe et al. 1995; Darwin and Tol 2001).

In the case of Denial or "*Laissez-faire*", PF and RF cause property losses (housing and business premises) because of the failure to protect or displace property prior to flooding. Thus, inhabitants are forced to migrate and relocate. These derelict urban areas become urban wastelands. The difference between the two scenarios lies in the time at which people migrate. The Denial scenario implies that SLR is not anticipated at all: housing and business premises are gradually abandoned because of permanent or recurrent flooding. Impacts are assessed by the replacement cost method on the basis of individual and collective housing values[4], respectively, and mean building values per size category. However, the "*Laissez-faire*" scenario considers a market-based adaptation and, as citizens anticipate SLR, housing and business premises are abandoned 10 years before being flooded. In this case, the number of people that migrate is slightly lower than in the Denial scenario (10 years population growth will occur outside the area at risk of flooding) and properties depreciate in value as a result of anticipation. We consider that knowing that the property will be flooded at a 10-years horizon implies an accelerated rate of financial depreciation of the capital asset located in a future flooded area. Expert judgment estimates that only 30% of the financial value of housing and businesses would remain. Negative amenities resulting from urban wasteland are not accounted for.

In the Retreat scenario, abandoned urban areas are assumed to be dismantled and people also migrate ten years before being flooded. In the Protection scenario, it is presumed that urban areas are fully protected and, therefore, the population density increases. In both cases, permanent and recurrent coastal flooding causes no damage to housing and business premises.

M1 assesses the impacts of an EF event in 2100 in terms of the number of people that may be affected and the damage to ground-floor housing and businesses. Impacts on infrastructure are not accounted for. Impacts are assessed using the damage functions developed in the French context. For ground-floor housing, impacts are estimated as a percentage of the property value. The percentage is a function of the water level in the building (Torterotot 1993). Damage functions of IIBRBS (1998) are used to assess the impacts on buildings used for professional purposes. A distinction is made between damage to equipment and stock, structural degradation and operational losses.

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[4] immobilier.com and terrain-construction.com consulted in March 2011

3.3 Agriculture (M2)

PF and RF are assumed to cause losses in agricultural land in the Denial, "*Laissez-faire*" and Retreat scenarios because farmland is submerged and transformed into wetlands, lagoons or marine ecosystems. Additional losses of agricultural land are expected due to (i) the relocation of urban areas that are flooded (3.2) and (ii) the migration of beaches and dunes, which encroach on agricultural land (3.4).

Economic impacts can be expressed as the sum of annual cropland rents between the year of flooding and 2100 (Fankhauser 1994). The mean agricultural land values per municipality are based on the figures for 2010 (2010 AGRESTE and SAFER databases: from €3,570 to €24,850/ha with an average of €9,700/ha) and a 10% return rate.

An EF event in 2100 may have several impacts on crops. Classic damage functions (Devaux-Ros 2000; SYMADREM 2010; Deleuze et al. 1991), which are generally used to assess the impact of floods on agricultural land, are adapted to integrate the additional impacts of salt on crops and soil (Agenais, 2010), on the basis of interviews with agricultural experts in the Languedoc-Roussillon region and in the Western France, which was affected by the storm, Xynthia, in February 2010. Damage functions distinguish (i) yield losses, (ii) rehabilitation tasks and (iii) damage to equipment. First, the value of yield losses is estimated as a percentage of revenue and operating costs per crop type (Chamber of Agriculture databases). Revenue is a function of yield (2008 AGRESTE database) and market price (2010 agricultural compensation grid, in the case of the natural disasters dataset). The percentage of losses is a function of crop type, soil type and the intensity of EF. Second, the costs of rehabilitation tasks are estimated as a function of the number of working hours. This depends on the crop type and the quantity of gypsum necessary to rehabilitate the agricultural land, which in turn depends on crop and soil types. Finally, the damage to equipment is estimated as a percentage of equipment values. This percentage is a function of the crop type, soil type and intensity of EF.

3.4 Beaches and dunes (M3)

Beaches and dunes are predominantly threatened by PF[5]. This is particularly the case in the urban context, where the coastal squeeze phenomenon may occur (Luisetti et al. 2008). As the sea level rises, the permanent infrastructure and buildings prevent the beaches and dunes from retreating. Where possible, beaches and dunes will migrate inland, encroaching on agricultural and natural areas. Major beach and dune losses are expected in

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[5] While RF and EF may also impact beaches and dunes by increasing erosion rates, data and knowledge were insufficient to build plausible assumptions for the evolution in erosion over the next few decades.

the Denial and "*Laissez-faire*" because urban assets remain (forming urban wasteland) after people have been forced to migrate inland. In the Denial scenario beach losses are only considered to be due to marine flooding because it is assumed that the towns and cities continue to implement traditional protection measures against erosion. In the "*Laissez-faire*" scenario, the state does not intervene further to limit beach losses. Therefore, additional beach losses due to erosion are expected (Rulleau et al. 2015). In the Denial and "*Laissez-Faire*" scenarios, the estimated area of beaches and dunes likely to disappear over time is calculated by crossing the PF water level with the regional high resolution Digital Elevation Model (LIDAR), the type of land use inland of the beach (urban, agricultural, natural) and the historic erosion/accretion rate (Brunel 2010). No loss of beaches or dunes is anticipated in the Protection scenario (we assume large-scale beach nourishment) or in the Retreat scenario (their evolution is assumed to be unconstrained).

The loss of beaches and dunes will inevitably affect the ecosystem services that they provide to society. This paper focuses on two services: storm protection and recreation. Associated values are based on the results of a contingent valuation survey conducted in 2009 in a pilot area of 12 km, located south of Montpellier. The area chosen is representative of urban and natural beaches along the Languedoc-Roussillon coastline. The storm protection service is estimated by Rulleau et al. (2015) at €229/household/year, which is equivalent to €4,588/household over a 20-year period. The recreation service is estimated at €36/household/year by Rulleau and Rey-Valette (2013), the equivalent of €728/household over a 20-year period. These values are then aggregated for the entire coastal area in the region with the total number of permanent and second homeowners (312,300 households) and the total number of permanent and seasonal residents, tourists and day trippers (3,360,000 households), divided by the total area of beaches and dunes likely to disappear. The calculation provides a value per hectare.

3.5 Lagoons (M4)

A rise in water levels may lead to lagoon expansion and a change in salinity (UNEP-MAP and RAC/SPA 2010), except for the Protection[6,7] scenario. Above all, these changes are likely to have an impact on water purification services[8]. Lagoons play a key role in diluting nitrogen (N) and phosphorus (P), originating from the watersheds located upstream. Shellfish growers, fishermen, swimmers and other recreational users may be affected by N and P if their concentrations are too high (above a threshold concentration) and lead to eutrophication phenomena. In a report to the European Commission, Ifremer (2001) defines five levels of eutrophication, the first and lowest

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[6] Under the Protection scenario, lagoon and wetland ecosystems are assumed to remain stable (Online Resource 2).

[7] Impacts of an EF event are not included in the analysis, they are considered to be negligible in comparison with PF and RF impacts because coastal wetland and lagoon ecosystems are resilient to EF.

being ‘no human impact on the level of eutrophication’ to the fifth and highest being ‘highly degraded by eutrophication’. We use the total Nitrate and Phosphorus concentration limits between the second and third level, where anoxic crises become recurrent instead of exceptional, as the threshold from which the impact of eutrophication is significant on users. Lagoon expansion will increase the volume of water, which may increase its capacity to dilute N and P. An increase in the volume of water is assessed as a function of the PF water level, lagoon depth and the historic siltation rate (Castaing 2008). N and P concentrations are assessed for each lagoon, with estimates of N and P fluxes that originate from the upstream watershed (local databases). Concentrations exceed threshold values (75 µmol N/L and 1.5 µmol P/L) for five lagoons. For these lagoons, the additional N and P fluxes that could be diluted by the increase in the lagoon volume are quantified and expressed in population equivalent (p.e.).

Associated economic values are estimated using the replacement cost method, based on the assumption that a treatment station would have to be built if this service did not exist. Investment costs range from €220 to €610/p.e.N and from €310 to €980/p.e.P as a function of the size of the station and a lifetime of 25 years, i.e. a mean annual cost of €9.4/p.e.N and €13.5/p.e.P (CGDD 2010).

3.6 Wetlands (M5)

PF and RF[6, 7] are expected to have different impacts on wetlands. PF wetlands are assumed to become marine or lagoon ecosystems. RF is likely to cause habitat transformation and/or migration, depending on how far the habitats are from the lagoon saltwater table (Kuhfuss et al. 2016). Similarly to beaches and dunes, in the case of the Denial and “*Laissez-faire*” scenarios, wetlands can only migrate onto flooded undeveloped areas (natural and agricultural land). In the Retreat scenario, wetlands can also shift onto adjacent former urban areas.

Wetlands are important for their biodiversity. Over 40 Natura 2000 habitats are represented in the study area. By crossing PF and RF maps with regional land use (SIG-LR 2006) and habitat types (Natura 2000 cartographic data), we identified 10 significant wetland habitats, which may be impacted (see Kuhfuss et al., 2016 for more details on these wetland habitats). This represents 78% of the regional wetland areas. This habitat classification provides the basis for the analysis conducted in M5. The services provided by each significant habitat are identified, according to the Millennium Ecosystem Assessment typology (MEA, 2005) and the Natura 2000 inventory. The habitat classification is then used to examine the losses and transformations of ecological habitats for each adaptation scenario, depending on the distance from the saltwater table (which, in turn, depends on elevation)[8]. Finally, the impact valuation is based on an analysis of the changes in the services provided by the wetlands as a result of habitat transformation. This paper considers two provisioning services (grazing and materials) and two regulating services (flood protection and water purification).

The values for provisioning services are estimated using market prices: the grazing service is valued as the mean gross margin for local pasture (€14/ha/year); materials provided (reeds) are valued at their local mean gross margin (€116/ha/year). Regulating services are valued in terms of benefit transfer using values from a meta-analysis of 89 wetland valuation studies (CGDD 2010): €438/ha/year for the flood protection service and €272/ha/year for the water purification service.

3.7 Coastal aquifers (M6)

SLR threatens coastal aquifers with saltwater intrusion. Two hydrogeologists in the region were consulted on the construction of a plausible scenario for saltwater intrusion in coastal aquifers at the 2100 time horizon. Two types of processes are considered:

(i) The brackish zone between fresh and saline groundwater ("saltwater wedge") may shift further inland as a result of PF and RF. Abstraction wells, previously located beyond the saline groundwater wedge zone, will then be situated in areas where upconing of the saline groundwater surface can easily occur (Oude Essink 2001). The shift of the saltwater wedge is characterised as a function of the SLR using the Ghyben and Drabbe (1889) and Herzberg (1901) relationships for the five unconfined coastal aquifers (four alluvial and one calcareous) located in the study area. Retreat and Protection options are not expected to impact the shift of the saltwater wedge;

(ii) Poorly protected abstraction wells will be exposed to the three types of coastal flooding (PF, RF and EF) and will allow saline water to percolate towards the aquifers. The groundwater wells that supply drinking water located in the PF and RF flooding areas are assumed to be relocated inland in the Retreat option and protected from PF and RF in the Protection scenario. However, the wells remain exposed to EF, regardless of the adaptation option.

In a context of water scarcity, like that of the Languedoc-Roussillon region, and with an expected increase in water demand in the near future (linked to the increase in population), saltwater intrusion would reduce the freshwater

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[8] The characterisation of physical impacts is based on interviews and working sessions with the stakeholders and scientific researchers actively involved in managing the lagoons and associated wetlands in the study area.

resources. This could affect provisioning services, such as the public water supply, water for irrigation and industrial uses. We focus our analysis on the public water supply, given that it is the principal use of groundwater in the coastal area. The replacement cost method is used to estimate the values associated with both types of processes for all three flooding categories. Calculations are based on the assumption that small desalination plants are installed to offset the decrease in fresh groundwater availability, with mean annual costs (including investment, operating costs and the environmental costs of CO2 emissions) ranging from €1.2 to €1.4/m3 (based on the analysis of the Worldwide Desalting Plants Inventory database provided by Zhou and Tol 2005).

3. RESULTS

First, a progressive SLR may lead to major land-use changes at the 2100 time horizon (except for the Protection scenario): the relocation or densification of urban areas, loss of agricultural land (-8,850 ha, equivalent to -10%), the increase in lagoon areas (+1,730 ha, a 5% rise) and the modification of wetlands (losses, migration or extension of ecosystems). Transition matrices (Table 2) present the type and magnitude of the changes for each scenario. They detail the evolution of each land-use type between 2010 and 2100. For instance, Table (a) illustrates that in the Denial scenario, 90% of the agricultural land remains agricultural; 3% is urbanised, 1% is replaced by beaches and dunes, 5% becomes wetlands and 1% is transformed into marine ecosystems. In 2100, agricultural areas occupy 91,050 ha or 10% less than in 2010. Overall, Denial and “*Laissez-faire*” scenarios lead to similar land-use changes, with the creation of 3,050 ha of urban wasteland and 3,500 ha of wetlands (a rise of 19%) and the loss of 360 to 570 ha (-11% to -17%) of beaches and dunes due to coastal squeeze. In the case of the Retreat scenario, abandoned urban areas are assumed to be dismantled, beaches and dunes evolve freely and wetlands expand (+5,640 ha, a rise of 30%).

Table 1. Methods for the quantification and monetary valuation of impacts due to progressive PF and RF, and to an EF in 2100

	Valuation module	Assets/ services	Impacts	Monetary valuation method
Progressive PF and RF	M1: Urban	Population	People forced to migrate/ to relocate	Not assessed
		Housing	Property losses	Replacement costs
		Businesses	Building losses	Replacement costs
	M2: Agriculture	Land	Land loss	Opportunity costs
	M3: Beaches and dunes	Storm protection	Decrease in the service due to beach and dune losses	Contingent valuation, value transfer and aggregation
		Recreation	Decrease in the service due to beach and dune losses	Contingent valuation, value transfer and aggregation
	M4: Lagoons	Water purification	Improvement in nitrogen (N) and phosphorus (P) dilution capacity	Replacement costs
	M5: Wetlands	Pastures	Increase/ decrease in the services due to wetland gains/ losses	Market price
		Reeds		Market price
		Flood protection		Value transfer
		Water purification		Value transfer
	M6: Coastal aquifers	Drinking water provision	Decrease in the service due to groundwater salinisation	Replacement costs
EF in 2100	M1: Urban	Population	Full-time inhabitants affected (people living in ground-floor accommodation)	Not assessed
			Secondary inhabitants affected	Not assessed
		Housing	Degradation of ground-floor	Damage functions
		Firms	Damage to equipment and stocks	Damage functions
			Structural degradation	
			Operating losses	
	M2: Agriculture	Crops and equipment	Yield losses	Damage functions
			Rehabilitation tasks	
			Damage to equipment	
	M6: Coastal aquifers	Drinking water provision	Decrease in the service due to groundwater salinisation	Replacement costs

Table 2. Transition matrices of land-use change (in ha) from 2010 to 2100 for each scenario for the 58 municipalities under study. Numbers in brackets show percentage, which refers to the total area for each land-use category in 2010 (row). Text in bold shows major differences between adaptation options.

(a) Denial

	2100								Total 2010
2010	Urban	Agriculture	Beaches and dunes	Forests and semi-natural	Lagoons	Wetlands	Urban wasteland	Sea	
Urban	20,536 (87)	-	-	-	-	**-**	**3,050 (13)**	**-**	23,586
Agriculture	3,050 (3)	81,050 (90)	447 (1)	-	-	4,602 (5)	-	751 (1)	89,900
Beaches and dunes	-	-	**2,052 (62)**	-	-	-	-	**1,256 (38)**	3,307
Forests and semi-natural	-	-	447 (1)	34,995 (93)	663 (2)	-	-	1,640 (4)	37,745
Lagoons	-	-	-	-	31,500 (100)	-	-	-	31,500
Wetlands	-	-	-	-	1,067 (6)	18,036 (94)	-	-	19,103
Total 2100	23,586	81,050	**2,946**	34,995	33,230	**22,638**	**3,050**	**3,647**	205,141
Total transition (ha)	-	-8,850	**-362**	-2,750	+1,730	**+3,535**	**+3,050**	**+3,647**	
Total transition (%)	-	-10	**-11**	-7	+5	**+19**	**+++**	**+++**	

(b) *"Laissez-faire"*

	2100								Total 2010
2010	Urban	Agriculture	Beaches and dunes	Forests and semi-natural	Lagoons	Wetlands	Urban wasteland	Sea	
Urban	20,536 (87)	-	-	-	-	**-**	**3,050 (13)**	**-**	23,586
Agriculture	3,050 (3)	81,050 (90)	447 (1)	-	-	4,602 (5)	-	751 (1)	89,900
Beaches and dunes	-	-	**1,842 (56)**	-	-	-	-	**1,466 (44)**	3,307
Forests and semi-natural	-	-	447 (1)	34,995 (93)	663 (2)	-	-	1,640 (4)	37,745
Lagoons	-	-	-	-	31,500 (100)	-	-	-	31,500
Wetlands	-	-	-	-	1,067 (6)	18,036 (94)	-	-	19,103
Total 2100	23,586	81,050	**2,736**	34,995	33,230	**22,638**	**3,050**	**3,857**	205,141
Total transition (ha)	-	-8,850	**-572**	-2,750	+1,730	**+3,535**	**+3,050**	**+3,857**	
Total transition (%)	-	-10	**-17**	-7	+5	**+19**	**+++**	**+++**	

(c) Retreat

	2100								Total 2010
2010	Urban	Agriculture	Beaches and dunes	Forests and semi-natural	Lagoons	Wetlands	Urban wasteland	Sea	
Urban	20,536 (87)	-	362 (2)	-	-	**2,107 (9)**	-	**582 (2)**	23,586
Agriculture	3,050 (3)	81,050 (90)	447 (1)	-	-	4,602 (5)	-	751 (1)	89,900
Beaches and dunes	-	-	**2,052 (62)**	-	-	-	-	**1,256 (38)**	3,307
Forests and semi-natural	-	-	447 (1)	34,995 (93)	663 (2)	-	-	1,640 (4)	37,745
Lagoons	-	-	-	-	31,500 (100)	-	-	-	31,500
Wetlands	-	-	-	-	1,067 (6)	18,036 (94)	-	-	19,103
Total 2100	23,586	81,050	**3,308**	34,995	33,230	**24,745**	**-**	**4,228**	205,141
Total transition (ha)	-	-8,850	**0**	-2,750	+1,730	**+5,642**	**-**	**+4,228**	
Total transition (%)	-	-10	**0**	-7	+5	**+30**	**-**	**+++**	

Second, these land-use changes will lead to major physical and economic impacts (Table 3). Economic impacts are expected to reach €19.5 billion in the case of Denial, with more than 80,000 people forced to migrate and relocate. The "cost of inaction" due to PF and RF represents on average €43,000 per inhabitant in 2010, or €140 million/km of coastline. Major impacts are expected from housing losses (80% of the total) and losses of beaches and dunes (15% of the total). This cost could be reduced by 50%, if SLR was anticipated by economic agents ("*Laissez-faire*"), and by 99%, if public adaptation options were planned in advance (Protection and Retreat), without considering adaptation costs. Negative SLR impacts on ecosystems are estimated at €3 billion in the Denial scenario (15% of the total) and could reach €4.7 billion in the "*Laissez-faire*" scenario (48% of the total). Total SLR impacts on ecosystems are positive in the Retreat scenario, as beaches, dunes and wetlands are expected to evolve in an unconstrained way and their total area would increase as a result of the coastal topography.

In addition, damage caused by an EF event that occurs in 2100 at the regional scale is expected to be 48% higher with SLR (€39.6 billion in the Denial scenario) than without (€26.7 billion) (Table 3). The exposed population is expected to be 63% higher (70,000 people in the Denial scenario with SLR compared to 43,000 without SLR). The "cost of inaction" in case of EF is, thus, estimated at €12.9 billion (€29,000/inhabitant or €56 million/km). This cost could be reduced by 91% if the Retreat option was implemented. In the Protection scenario, if protection efforts fail, economic impacts could be four times higher than without SLR (€104.6 billion).

Table 3. SLR impacts due to progressive PF and RF between 2010 and 2100, and in case of EF in 2100, for each scenario

			Physical impacts						Economic impacts[a] (10^{6} €)				
	Valuation module	Assets/services	Unit	Without SLR	Denial	*"Laissez-faire"*	Protection [b]	Retreat	Without SLR	Denial	*"Laissez-faire"*	Protection [b]	Retreat
Progressive PF and RF between 2010 and 2100	M1: Urban	Population	people	-	83,000	77,000	-	77,000	-	n.a.	n.a.	-	n.a.
		Housing	number	-	37,000	37,000	-	-	-	-15,720	-4,716	-	-
		Businesses	number	-	4,600	4,600	-	-	-	-577	-173	-	-
	M2: Agriculture	Land	ha	-	-8,850	-8,850	-	-8,850	-	-245	-245	-	-245
	M3: Beaches and dunes	Storm protection	ha	-	-362	-572	-	-	-	-1,158	-1,830	-	-
		Recreation	ha	-	-362	-572	-	-	-	-1,810	-2,860	-	-
	M4: Lagoons	Water purification	p.e.N p.e.P	- -	85,740 22,370	85,740 22,370	n.a. n.a.	85,740 22,370	-	+48	+48	n.a.	+48
	M5: Wetlands	Pastures	ha	-	4,486	4,486	n.a.	7,042	-	+3	+3	n.a.	+4
		Reeds	ha	-	2,718	2,718	n.a.	3,923	-	+14	+14	n.a.	+20
		Flood protection	ha	-	4,845	4,845	n.a.	7,512	-	+92	+92	n.a.	+143
		Water purification	ha	-	4,134	4,134	n.a.	6,692	-	+49	+49	n.a.	+79
	M6: Coastal aquifers	Drinking water provision	m^{3}	-	7,400,000	7,400,000	5,800,000	5,800,000	-	-204	-204	-160	-160
	TOTAL PF and RF								-	-19,508	-9,822	-160	-111
	Including impacts on ecosystem services								-	-2,966	-4,688	-160	+134
									-	15%	48%	100%	
EF in 2100	M1: Urban	Permanent population	people	32,000	52,000	52,000	104,000	22,000	n.a.	n.a.	n.a.	n.a.	n.a.
		Seasonal population	people	11,000	18,000	18,000	36,000	7,100	n.a.	n.a.	n.a.	n.a.	n.a.
		Housing	number	14,400	23,000	23,000	46,300	9,800	-26,219	-38,822	-38,822	-129,106	-27,000
		Businesses	number	3,100	4,500	4,500	9,100	4,500	-490	-673	-673	-1,647	-673
	M2: Agriculture	Crops and equipment	ha	9,900	13,100	13,100	24,600	13,100	-17	-36	-36	-59	-36
	M6: Coastal aquifers	Drinking water provision	m^{3}	-	1,500,000	1,500,000	3,100,000	1,500,000	-	-56	-56	-114	-56
	TOTAL EF in 2100								-26,726	-39,587	-39,587	-130,926	-27,765
	Impacts of SLR in case of EF in 2100									-12,861	-12,861	-104,200	-1,039
	Increase in comparison with the situation without SLR									+48%	+48%	+390%	+4%

Note: n.a.: not assessed; p.e.N: person equivalent nitrogen; p.e.P.: person equivalent phosphorous

[a] Economic impacts are **not discounted** and measured in constant 2010 euros; [b] For EF: in case protection works fail

4. DISCUSSION

5.1 The benefits of anticipating and adapting

These results can be used to assess the benefits of anticipating and adapting to SLR for the 2010-2100 period. By comparing the Retreat and Denial scenarios, the total benefits of public adaptation planned in advance could amount to €31.2 billion (€19.4 and €11.8 billion due to PF/RF and EF, respectively), i.e. €69,000 per inhabitant of the study area in 2010 or €135 million/km of coastline. These figures highlight the importance of raising awareness levels of public services and coastal managers to SLR, in order to limit the damage caused by SLR. The effects of SLR will emerge slowly from 2040 onwards and then accelerate after 2080, given the topography of the study area: the current generation of managers and decision-makers may deny the existence of the risk. Nevertheless, some decisions have to be taken early and the need to conduct research on new technologies and economic instruments is immediate.

Anticipating and adapting to SLR may also carry high social and economic costs, depending on the option, which should be compared to the benefits. Examples of adaptation measures in Languedoc-Roussillon provide some cost estimates for the Protection and Retreat scenarios. However, further research is necessary in order to assess the costs of adaptation at a regional level:

- The first beach nourishment in the region was implemented in 2008 in the Aigues-Mortes Gulf, on 10 km of beaches. The initial cost was €8.7 million and the cost of maintenance is €1 million every 10 years. We estimate that similar large-scale beach nourishment would cost around €253 million, if it was implemented along the full 161 km of beaches in the region. A regional study conducted by CETE Méditerranée (2010) provides estimates of the costs for protecting the regional coastline from increasing erosion with a combination of measures outlined in the retreat scenario, as well as soft and hard protection measures. Total costs are estimated at €351 million at the 2040 time horizon. If extrapolated to the 2100 time horizon, they could reach at least €1 billion.
- To our knowledge, there are no examples of strategic, anticipatory and planned large-scale relocation for developed structures and activities, which could serve as a basis for assessing the cost of implementing the Retreat scenario. In the Languedoc-Roussillon region, in 2010, a road was relocated (strategic retreat) along 12 km of coastline between Sète and Marseillan, at a total cost of €55 million. This adaptation measure would cost €545 million if all the roads along the entire length (70 km) of Languedoc-Roussillon's natural beaches were relocated. However, this example is not representative of urban areas, where built assets (houses, apartments, business premises) would have to be relocated. André et al (2016) have designed an economic

> assessment based on a fictional site that constitutes an archetypal seaside community on the French Mediterranean coast. It represents a dense urban area with individual houses and apartments, as well as tourist-related businesses, located on a low-lying, sandy coastline and exposed to the risk of erosion and coastal flooding. They estimate that the full relocation of 650 inhabitants would cost between €62 and €150 million (€100,000 to 231,000 per relocated inhabitant). Based on these figures, we estimate that the relocation of all urban areas in zones exposed to PF and RF (77,000 inhabitants) would cost between €7.7 and €17.8 billion.

Other criteria should also be incorporated into the decision-making, such as sustainability, equity (Clément et al. 2015) and affordability (Fletcher et al. 2016). For instance, the sustainability of massive beach nourishment, assumed to be carried out in the Protection scenario, could be called into question: maintenance measures should be conducted at 10 year intervals in order to reshape the beaches; locating and sustainably managing a reserve of sand is problematic. In our analysis, the Retreat scenario appears to be the best scenario for ecosystems. However, it also raises several issues, including solidarity between local councils: the risk of coastal flooding may potentially affect large areas in some municipalities, who lack sufficient land to relocate their population, housing and economic activities. At the regional scale, four municipalities with a total of 62,000 inhabitants would face this problem.

5.2 The weight of coastal ecosystem services

Our results underline the importance of incorporating coastal ecosystems into the assessment of adaptation scenarios. First, neglecting coastal ecosystems in the design of adaptation options may lead to the decrease and/or degradation of some ecosystem services as a result of marine flooding and coastal squeeze (loss of 44% of beach areas in the "*Laissez-faire*" scenario). In coastal areas, such as the Languedoc-Roussillon region, the potential negative economic impacts associated to these changes in ecosystem services are considerable: they represent 48% of the total economic impacts in the "*Laissez-faire*" scenario. Local residents, day trippers and tourist activities may also be affected by these changes. The valuation of impacts on wetlands also shows that, although the extension of wetland areas is expected to generate positive economic benefits in each adaptation scenario, they are maximal in the Retreat scenario. Thus, classic cost-benefit analyses used to rank alternative adaptation options may underestimate the benefits associated to adaptation in some situations because, in general, they do not account for ecosystem services. Second, some coastal ecosystems could play a key role in reducing the vulnerability of coastal communities in the event of marine flooding and storms. In our study area, we show that maintaining beaches and dunes, by avoiding coastal squeeze, is a valuable preventive measure that is likely to reduce the need for expensive engineering works in some locations (Spalding et al. 2014). However, it is not common practice for public services, coastal managers and engineering companies to incorporate ecosystem services in the economic valuation framework. A stepwise knowledge-sharing process should be set up before the integration of ecosystem services in the policy decision-making framework can be envisaged. Further research should also be conducted to improve our understanding of the impact of SLR on coastal ecosystems (groundwater, beaches and dunes, lagoons and wetlands) and to develop ecosystem-based adaptation strategies.

5.3 An introduction to foresight approaches

The four adaptation scenarios considered in this article are theoretical. We consider that the implementation of adaptation options is uniform along the regional coastline. However, in practice, adaptation is place- and context-specific (Field et al. 2014): adaptation options are likely to consist of a spatial and temporal policy mix. Our narrative scenarios and the principal quantitative results of the economic impact analysis were used to introduce a 1-day foresight workshop held in June 2012, entitled *"What coastline for the 2010-2050 Languedoc-Roussillon?"* (Montpellier, France). The workshop was organised by the regional authorities and brought together 105 regional experts and stakeholders. Participants were organised into three groups and were asked to adapt and combine various options in order to build plausible adaptation pathways at the regional scale. The resulting scenarios involved two types of combination of "*Laissez-faire*" and Retreat scenarios: (i) the "organised *Laissez-faire*" or "voluntary Retreat" implements both options simultaneously; and (ii) the "two-step Retreat", which implements the "*Laissez-faire*" scenario first and then the Retreat scenario, as a way to make the Retreat scenario more acceptable. The same approach could be implemented locally (in groups of municipalities). This would probably lead to different combinations of approaches, which would depend on the local environmental, as well as the economic and social contexts, not to mention the outcomes of negotiations and compromise solutions.

5. CONCLUSION

Major land-use changes are expected due to SLR at the 2100 time horizon: relocation or densification of urban areas, loss of agricultural land, increase in lagoon areas and modification of wetlands (losses, migration or extension). The total benefit of public adaptation options that are planned in advance could reach €31.2 billion, i.e. €69,000 per inhabitant of the study area in 2010 or €135 million/km of coastline. This valuation is obviously not exhaustive (many ecosystem services and damage to infrastructure are not valued). Therefore, our results should be considered as lower bound estimates. Our findings highlight the importance of (i) raising awareness to ensure that public services and coastal managers can anticipate the consequences of SLR and (ii) incorporating coastal ecosystems into the assessment of the adaptation options. They may be used as an aid for participatory foresight approaches. They could help public services and coastal managers anticipate and plan proactively for SLR: by identifying the ecosystems, coastal populations, infrastructure, agriculture and water resources that should be relocated due to the impacts of SLR; by identifying potential future conflicts among municipalities (for instance caused by the decrease in the availability and/or supply of land and water resources); and by raising awareness of the impacts of SLR on coastal natural habitats and municipalities. Further research is required to develop legal, governance and economic tools that could be used to implement adaptation. An analysis of the feasibility and acceptability of the different options for the local population and decision-makers is also essential.

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Electronic supplementary material

ESM_1. Details on the valuation functions per module

ESM_2. Schematic representation of the four adaptation scenarios for the coastal area