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

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11

12 **Abstract**

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

27

28

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

1 1. INTRODUCTION

2 Coastal systems and low-lying areas will be increasingly at risk from flooding in the 21st century as a result of a
3 progressive sea level rise (SLR) and extreme flooding (Wong et al. 2014). Assessing the vulnerability of coastal
4 zones to SLR has become an increasingly important field of research since the 1980s. Yohe (1990) and Titus
5 (1990) were among the first to analyse the consequences of this phenomenon. They investigated the economic
6 vulnerability of coastal areas to a 0.5 to 2 m SLR at the scale of the United States.

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

15 SLR could impact the coastal area in several ways (Wong et al. 2014). In urban and agricultural areas, SLR may
16 force people to migrate. It may cause loss or damage to crops, land, housing and buildings. In addition, SLR may
17 have an impact on ecosystems, such as beach loss, lagoon extension, wetland migration and groundwater
18 salinisation. The economic impact of SLR generally focuses on urban and agricultural areas. Little research has
19 been done to assess the economic impacts of SLR on ecosystems. In general, existing studies focus on
20 characterising the physical impacts of SLR with regard to a particular coastal ecosystem (see for instance:
21 Monioudi et al. 2014 for beaches; Craft et al. 2009 for wetlands; Li et al. 2015 for mangroves), without considering
22 the associated economic impacts. Failure to take account of the economic impact means that the latter cannot be
23 put into perspective with other expected impacts. However, coastal ecosystems are essential components of coastal
24 areas. By providing a variety of ecosystem services, they make a significant contribution to the welfare of residents,
25 tourists and day trippers (MEA 2005). The loss or transformation of coastal ecosystems resulting from SLR could
26 affect ecosystem services and, therefore, have an impact on human well-being. As underlined by Lin et al. (2014)
27 *“any assessment that incorporates only goods with market proxies (such as property, human health, or economic
28 production) risks seriously underestimating both the costs and the benefits of the adaptation options”*. Thus,
29 analysing the impacts of SLR on coastal ecosystems and the services they provide could be beneficial for coastal
30 managers when it comes to raising awareness about the need to anticipate SLR and choose the best strategy for

1 adaptation. Overall, the IPCC (Wong et al. 2014) claims that the economics of coastal adaptation are under-
2 researched and that more comprehensive assessments are needed for the valuation of coastal ecosystem services.
3 In this perspective, the article aims to provide a comprehensive assessment of the benefits of adapting to SLR at a
4 regional scale. It proposes an innovative approach that integrates coastal ecosystem services, as well as urban and
5 agricultural assets, within the valuation framework. We simulate the impacts of a gradual 1 m rise in sea level over
6 the 21st century and an extreme flooding event in 2100 for four contrasted adaptation scenarios (Denial, “*Laissez-*
7 *faire*”, Protection and Retreat). We study the gradual impacts of loss of land and land-use changes, and other
8 impacts due to SLR such as saltwater intrusion. The assessment involves coupling the results of hazard-modelling
9 approaches with various economic valuation methods, including direct damage functions and valuation methods
10 used in environmental economics. Our objective is to estimate the potential benefits of adapting to SLR to help
11 decision makers discussing the possible consequences of the different adaptation options.

12

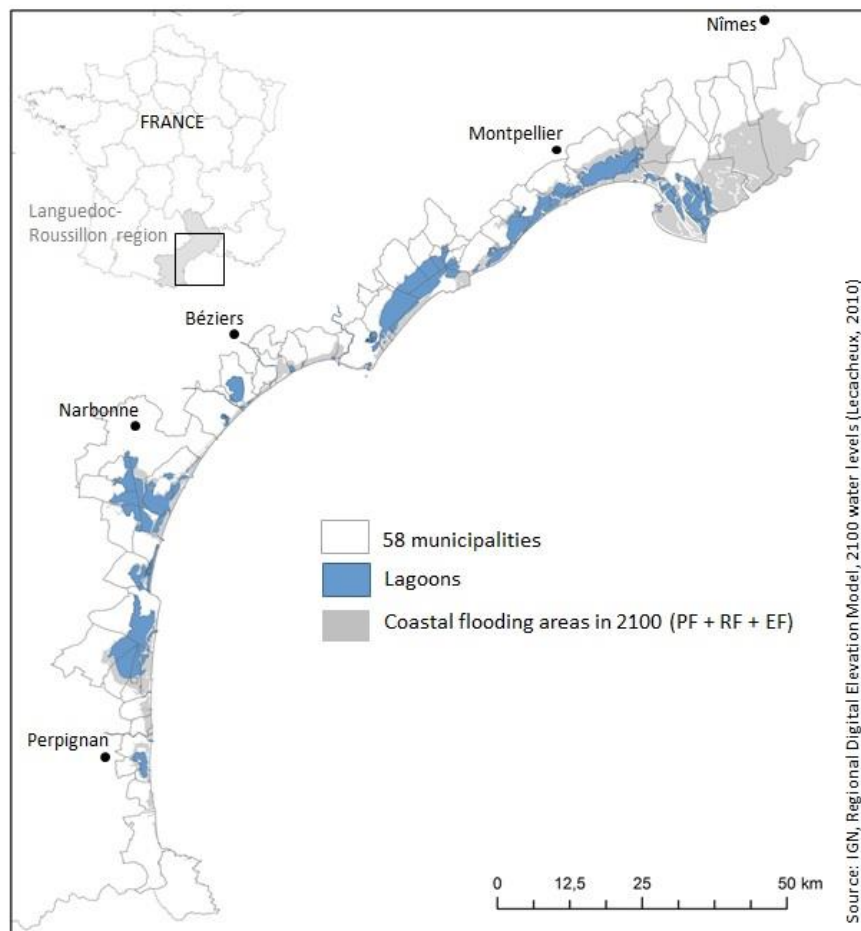
13 **2. SLR AND ADAPTATION OPTIONS FOR THE FRENCH MEDITERRANEAN SANDY** 14 **COASTLINE**

15 **2.1 The French Mediterranean sandy coastline**

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

24 Currently, sandy beaches make up 70% of the coastline and alternate with built-up areas. Regional Mediterranean
25 wetlands represent 17% of all French wetlands of international importance (CGDD 2010). Almost all of them are
26 community interest habitats under the European Habitats Directive and belong to the Natura 2000 network. Six
27 aquifers located in the coastal area are of regional importance, representing 100 million cubic metres of
28 groundwater, which provides 32% of the regional drinking-water supply (AERMC). Agricultural land accounts

1 for 42% of the study area (SIG-LR¹) and is dominated by vineyards, followed by cereals, fruit and vegetables,
2 grassland and rice.



3

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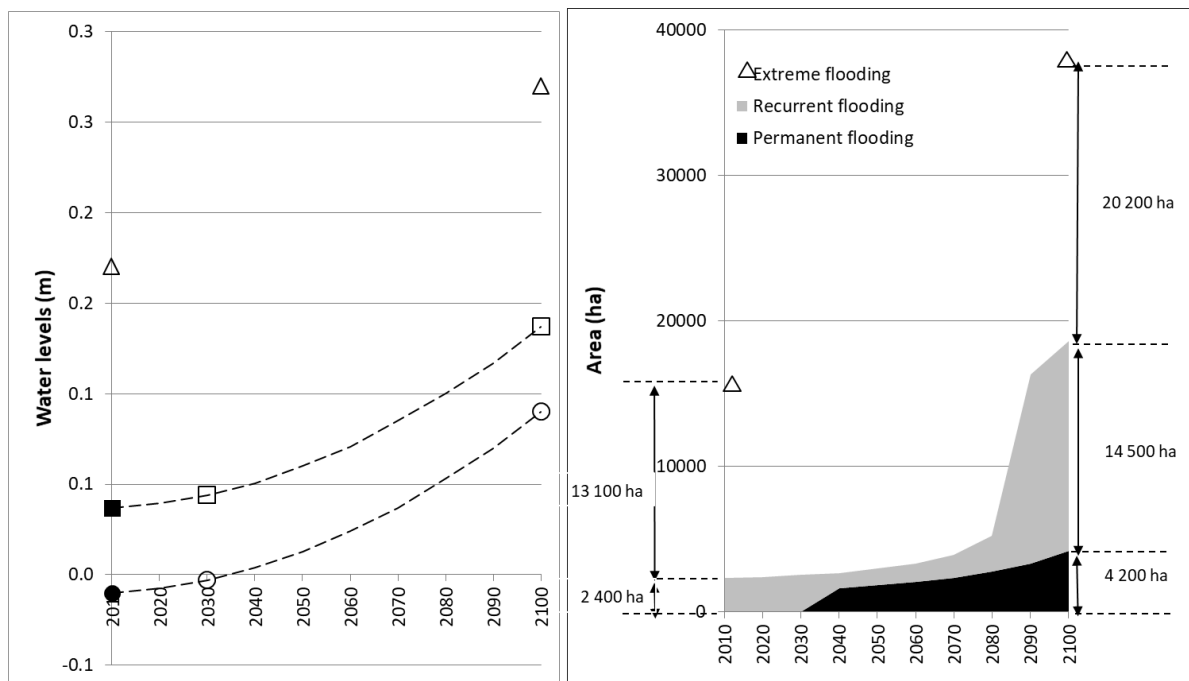
Fig. 1 Study area

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

¹ <http://www.siglr.org/>

1 2.2 Impacts of SLR on coastal flooding areas

2 Climate change and a gradual SLR are expected to increase these expenses due to marine flooding in the coming
 3 decades. Adapting the IPCC (Wong et al. 2014) hypotheses to the case of the Languedoc-Roussillon gives a worst-
 4 case scenario, with a 1 m rise in sea level by 2100 and greater storm impact due to higher water levels. Figure 2
 5 presents the expected change in water levels for three return periods in relation to coastal flooding (Lecacheux et
 6 al. 2010): (i) permanent flooding (PF) (area flooded 100% of the time), which corresponds to the mean
 7 meteorological conditions and the lowest astronomical tides; (ii) recurrent flooding (RF) (area flooded at least
 8 twice a year), which corresponds to the mean annual meteorological conditions and the highest astronomical tides;
 9 and (iii) extreme flooding (EF), which corresponds to a 100-year return period for a winter storm surge (the winter
 10 1982 storm is used as the reference).



11
 12 **Fig. 2** Evolution of (a) water levels and (b) coastal flooding area resulting from PF, RF and EF over time.

13 Legend (a): observed (●) and simulated (○) permanent water level; observed (■) and simulated (□) recurrent
 14 water level; average simulated extreme water level (Δ); --- extrapolation of permanent and recurrent water levels
 15 over time (polynomial trend curve).

16 Crossing simulated water levels with the regional Digital Elevation Model (Lecacheux et al., 2010) shows that the
 17 coastal areas affected by SLR will increase slowly until 2080. From then on, the rate of increase is expected to
 18 accelerate because of the topography of the study area. The coastal areas affected by PF or RF are likely to increase
 19 by a factor of 3.5 between 2080 and 2100 (Figure 2). In 2100, 58 coastal municipalities (Figure 1) may be exposed
 20 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

1 permanently flooded. Results also show that in 2100, EF is likely to affect a larger area (20,200 ha, an area 55%
2 greater). This is quite distinct from the area affected by EF in 2010. Overall, almost 39,000 ha may be exposed to
3 coastal flooding in 2100 compared to 15,000 ha in a situation without SLR.

4 5 **2.3 Potential adaptation options**

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

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

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

1 “*Laissez-faire*” options). These options are likely to have a severe impact on future generations over the period
2 2080-2100. It takes time to implement adaptation strategies for SLR. Raising the awareness of citizens and elected
3 representatives about the benefits of such different options may be helpful to initiate the design of adaptation
4 pathways at the regional level.

5

6 **3. METHOD**

7 **3.1 Overview of the valuation framework**

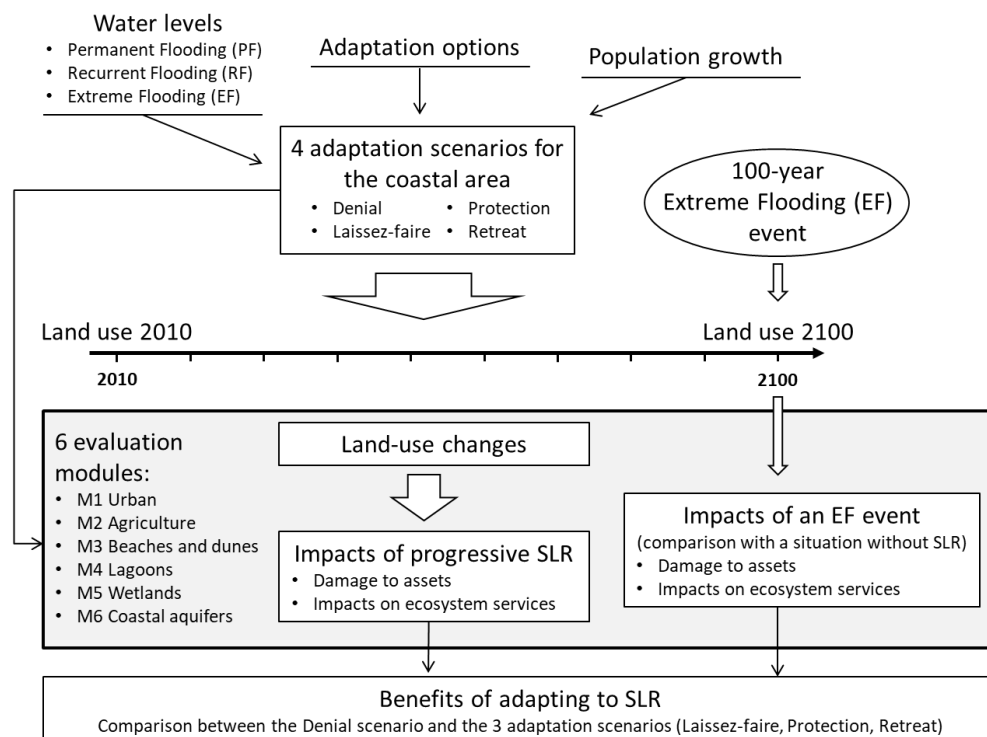
8 We propose a valuation framework to assess the benefits of these four contrasted management options. The
9 framework is organised into five main steps (Figure 3):

- 10 ▪ Step 1 consists of building narrative scenarios for the coastal area at the 2100 horizon. We consider that the
11 changes affecting the coastal area will predominantly be driven by (i) the evolution in water levels, (ii) the
12 option chosen to adapt to SLR and (iii) population growth (assumed to remain constant in the study area, with
13 a linear increase based on INSEE 1988-2006 statistics). Narrative scenarios were built during a 2-day project
14 meeting² between scientific researchers from a broad range of disciplines (sedimentology, geography,
15 sociology, economics and agronomy). As a result, four adaptation scenarios (one for each of the adaptation
16 options discussed in 2.3), describe the plausible evolutions likely to affect the coastal area. The scenarios make
17 assumptions about the associated land-use changes (Online Resource 2).
- 18 ▪ Step 2 provides quantitative estimates of land-use changes for each scenario in the 58 municipalities exposed
19 to coastal flooding. The following categories of land use are considered: urban, agricultural, forest and semi-
20 natural, lagoons, wetlands, beaches and dunes. The 2006 regional land cover GIS database SIG-LR³,
21 completed by Natura 2000 database, provides the basis for the analysis. Curves depicting the evolution of the
22 coastal flooding area due to PF and RF (Figure 2) are used to quantify the areas gained or lost by each land-
23 use category over time.
- 24 ▪ Step 3 consists of understanding the impacts of PF and RF during the 2010-2100 period for each land-use
25 category and adaptation scenario. The impacts are described in terms of (i) damage to assets located in urban
26 and agricultural areas and (ii) changes in the services provided by coastal ecosystems. First, they are
27 characterised in physical terms before being assessed in economic terms. We assume that the number of assets

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

³ <http://www.siglr.org/>

- 1 and the importance of ecosystem services are proportional to the corresponding land-use category. In other
 2 words, the impacts can be linked to the area gained or lost due to PF and RF over time.
- 3 ■ Step 4 involves the characterisation of the physical impacts and an economic valuation of an EF event that
 4 occurs in 2100. The impact assessment of an EF event in 2100 is based on the EF area with the 2100 projected
 5 land use for each scenario and provides a comparison with a situation with no SLR.
- 6 ■ Step 5 assesses the benefits of adapting to SLR. It compares the impacts of progressive SLR and an EF event
 7 (in 2100) in the Denial scenario with the three other adaptation scenarios.



8
 9 **Fig. 3** Diagram describing the valuation framework

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

16
 17 **3.2 Urban (M1)**

18 In urban areas, M1 considers that PF and RF will force people to migrate and will cause loss or damage to land,
 19 housing and businesses if no protective measures are implemented. The analysis excludes the impacts on

1 infrastructure (roads, bridges, railways). It is assumed that progressively flooded urban areas (in the Denial,
2 “*Laissez-faire*” and Retreat options) are relocated beyond the EF zone, onto predominantly agricultural land in the
3 same municipality, as far as possible. The economic cost of urban land loss is assessed at its opportunity cost, i.e.
4 the value of interior agricultural land (3.3) and not the value of urban coastland (Yohe et al. 1995; Darwin and Tol
5 2001).

6 In the case of Denial or “*Laissez-faire*”, PF and RF cause property losses (housing and business premises) because
7 of the failure to protect or displace property prior to flooding. Thus, inhabitants are forced to migrate and relocate.
8 These derelict urban areas become urban wastelands. The difference between the two scenarios lies in the time at
9 which people migrate. The Denial scenario implies that SLR is not anticipated at all: housing and business premises
10 are gradually abandoned because of permanent or recurrent flooding. Impacts are assessed by the replacement cost
11 method on the basis of individual and collective housing values⁴, respectively, and mean building values per size
12 category. However, the “*Laissez-faire*” scenario considers a market-based adaptation and, as citizens anticipate
13 SLR, housing and business premises are abandoned 10 years before being flooded. In this case, the number of
14 people that migrate is slightly lower than in the Denial scenario (10 years population growth will occur outside the
15 area at risk of flooding) and properties depreciate in value as a result of anticipation. We consider that knowing
16 that the property will be flooded at a 10-years horizon implies an accelerated rate of financial depreciation of the
17 capital asset located in a future flooded area. Expert judgment estimates that only 30% of the financial value of
18 housing and businesses would remain. Negative amenities resulting from urban wasteland are not accounted for.
19 In the Retreat scenario, abandoned urban areas are assumed to be dismantled and people also migrate ten years
20 before being flooded. In the Protection scenario, it is presumed that urban areas are fully protected and, therefore,
21 the population density increases. In both cases, permanent and recurrent coastal flooding causes no damage to
22 housing and business premises.

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

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

1 **3.3 Agriculture (M2)**

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

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

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

23

24 **3.4 Beaches and dunes (M3)**

25 Beaches and dunes are predominantly threatened by PF⁵. This is particularly the case in the urban context, where
26 the coastal squeeze phenomenon may occur (Luisetti et al. 2008). As the sea level rises, the permanent
27 infrastructure and buildings prevent the beaches and dunes from retreating. Where possible, beaches and dunes
28 will migrate inland, encroaching on agricultural and natural areas. Major beach and dune losses are expected in

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.

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

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

21

22 **3.5 Lagoons (M4)**

23 A rise in water levels may lead to lagoon expansion and a change in salinity (UNEP-MAP and RAC/SPA 2010),
24 except for the Protection^{6,7} scenario. Above all, these changes are likely to have an impact on water purification
25 services⁸. Lagoons play a key role in diluting nitrogen (N) and phosphorus (P), originating from the watersheds
26 located upstream. Shellfish growers, fishermen, swimmers and other recreational users may be affected by N and
27 P if their concentrations are too high (above a threshold concentration) and lead to eutrophication phenomena. In
28 a report to the European Commission, Ifremer (2001) defines five levels of eutrophication, the first and lowest

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.

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

11 Associated economic values are estimated using the replacement cost method, based on the assumption that a
12 treatment station would have to be built if this service did not exist. Investment costs range from €220 to €610/p.e.N
13 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
14 cost of €9.4/p.e.N and €13.5/p.e.P (CGDD 2010).

15

16 **3.6 Wetlands (M5)**

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

22 Wetlands are important for their biodiversity. Over 40 Natura 2000 habitats are represented in the study area. By
23 crossing PF and RF maps with regional land use (SIG-LR 2006) and habitat types (Natura 2000 cartographic data),
24 we identified 10 significant wetland habitats, which may be impacted (see Kuhfuss et al., 2016 for more details on
25 these wetland habitats). This represents 78% of the regional wetland areas. This habitat classification provides the
26 basis for the analysis conducted in M5. The services provided by each significant habitat are identified, according
27 to the Millennium Ecosystem Assessment typology (MEA, 2005) and the Natura 2000 inventory. The habitat
28 classification is then used to examine the losses and transformations of ecological habitats for each adaptation

1 scenario, depending on the distance from the saltwater table (which, in turn, depends on elevation)⁸. Finally, the
2 impact valuation is based on an analysis of the changes in the services provided by the wetlands as a result of
3 habitat transformation. This paper considers two provisioning services (grazing and materials) and two regulating
4 services (flood protection and water purification).

5 The values for provisioning services are estimated using market prices: the grazing service is valued as the mean
6 gross margin for local pasture (€14/ha/year); materials provided (reeds) are valued at their local mean gross margin
7 (€116/ha/year). Regulating services are valued in terms of benefit transfer using values from a meta-analysis of 89
8 wetland valuation studies (CGDD 2010): €438/ha/year for the flood protection service and €272/ha/year for the
9 water purification service.

10

11 **3.7 Coastal aquifers (M6)**

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

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

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

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

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.

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

8

9 **3. RESULTS**

10 First, a progressive SLR may lead to major land-use changes at the 2100 time horizon (except for the Protection
11 scenario): the relocation or densification of urban areas, loss of agricultural land (-8,850 ha, equivalent to -10%),
12 the increase in lagoon areas (+1,730 ha, a 5% rise) and the modification of wetlands (losses, migration or extension
13 of ecosystems). Transition matrices (Table 2) present the type and magnitude of the changes for each scenario.
14 They detail the evolution of each land-use type between 2010 and 2100. For instance, Table (a) illustrates that in
15 the Denial scenario, 90% of the agricultural land remains agricultural; 3% is urbanised, 1% is replaced by beaches
16 and dunes, 5% becomes wetlands and 1% is transformed into marine ecosystems. In 2100, agricultural areas
17 occupy 91,050 ha or 10% less than in 2010. Overall, Denial and “*Laissez-faire*” scenarios lead to similar land-use
18 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
19 360 to 570 ha (-11% to -17%) of beaches and dunes due to coastal squeeze. In the case of the Retreat scenario,
20 abandoned urban areas are assumed to be dismantled, beaches and dunes evolve freely and wetlands expand
21 (+5,640 ha, a rise of 30%).

1
2

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

3

1 **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,
 2 which refers to the total area for each land-use category in 2010 (row). Text in bold shows major differences between adaptation options.

3

(a) Denial

2010	2100								Total 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	+++	+++	

4

(b) "Laissez-faire"

2010	2100								Total 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	+++	+++	

5

1

(c) Retreat

2010	2100								Total 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	-	+++	

2

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

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

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

2

	Valuation module	Assets/services	Unit	Physical impacts					Economic impacts ^a (10 ⁶ €)				
				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	-	85,740	85,740	n.a.	85,740	-	+48	+48	n.a.	+48
			p.e.P	-	22,370	22,370	n.a.	22,370	-				
	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%	

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

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

1 4. DISCUSSION

2 5.1 The benefits of anticipating and adapting

3 These results can be used to assess the benefits of anticipating and adapting to SLR for the 2010-2100 period. By
4 comparing the Retreat and Denial scenarios, the total benefits of public adaptation planned in advance could
5 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
6 the study area in 2010 or €135 million/km of coastline. These figures highlight the importance of raising awareness
7 levels of public services and coastal managers to SLR, in order to limit the damage caused by SLR. The effects of
8 SLR will emerge slowly from 2040 onwards and then accelerate after 2080, given the topography of the study
9 area: the current generation of managers and decision-makers may deny the existence of the risk. Nevertheless,
10 some decisions have to be taken early and the need to conduct research on new technologies and economic
11 instruments is immediate.

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

- 16 - The first beach nourishment in the region was implemented in 2008 in the Aigues-Mortes Gulf, on 10 km of
17 beaches. The initial cost was €8.7 million and the cost of maintenance is €1 million every 10 years. We
18 estimate that similar large-scale beach nourishment would cost around €253 million, if it was implemented
19 along the full 161 km of beaches in the region. A regional study conducted by CETE Méditerranée (2010)
20 provides estimates of the costs for protecting the regional coastline from increasing erosion with a combination
21 of measures outlined in the retreat scenario, as well as soft and hard protection measures. Total costs are
22 estimated at €351 million at the 2040 time horizon. If extrapolated to the 2100 time horizon, they could reach
23 at least €1 billion.
- 24 - To our knowledge, there are no examples of strategic, anticipatory and planned large-scale relocation for
25 developed structures and activities, which could serve as a basis for assessing the cost of implementing the
26 Retreat scenario. In the Languedoc-Roussillon region, in 2010, a road was relocated (strategic retreat) along
27 12 km of coastline between Sète and Marseillan, at a total cost of €55 million. This adaptation measure would
28 cost €545 million if all the roads along the entire length (70 km) of Languedoc-Roussillon's natural beaches
29 were relocated. However, this example is not representative of urban areas, where built assets (houses,
30 apartments, business premises) would have to be relocated. André et al (2016) have designed an economic

1 assessment based on a fictional site that constitutes an archetypal seaside community on the French
2 Mediterranean coast. It represents a dense urban area with individual houses and apartments, as well as tourist-
3 related businesses, located on a low-lying, sandy coastline and exposed to the risk of erosion and coastal
4 flooding. They estimate that the full relocation of 650 inhabitants would cost between €62 and €150 million
5 (€100,000 to 231,000 per relocated inhabitant). Based on these figures, we estimate that the relocation of all
6 urban areas in zones exposed to PF and RF (77,000 inhabitants) would cost between €7.7 and €17.8 billion.
7 Other criteria should also be incorporated into the decision-making, such as sustainability, equity (Clément et al.
8 2015) and affordability (Fletcher et al. 2016). For instance, the sustainability of massive beach nourishment,
9 assumed to be carried out in the Protection scenario, could be called into question: maintenance measures should
10 be conducted at 10 year intervals in order to reshape the beaches; locating and sustainably managing a reserve of
11 sand is problematic. In our analysis, the Retreat scenario appears to be the best scenario for ecosystems. However,
12 it also raises several issues, including solidarity between local councils: the risk of coastal flooding may potentially
13 affect large areas in some municipalities, who lack sufficient land to relocate their population, housing and
14 economic activities. At the regional scale, four municipalities with a total of 62,000 inhabitants would face this
15 problem.

16

17 **5.2 The weight of coastal ecosystem services**

18 Our results underline the importance of incorporating coastal ecosystems into the assessment of adaptation
19 scenarios. First, neglecting coastal ecosystems in the design of adaptation options may lead to the decrease and/or
20 degradation of some ecosystem services as a result of marine flooding and coastal squeeze (loss of 44% of beach
21 areas in the “*Laissez-faire*” scenario). In coastal areas, such as the Languedoc-Roussillon region, the potential
22 negative economic impacts associated to these changes in ecosystem services are considerable: they represent 48%
23 of the total economic impacts in the “*Laissez-faire*” scenario. Local residents, day trippers and tourist activities
24 may also be affected by these changes. The valuation of impacts on wetlands also shows that, although the
25 extension of wetland areas is expected to generate positive economic benefits in each adaptation scenario, they are
26 maximal in the Retreat scenario. Thus, classic cost-benefit analyses used to rank alternative adaptation options
27 may underestimate the benefits associated to adaptation in some situations because, in general, they do not account
28 for ecosystem services. Second, some coastal ecosystems could play a key role in reducing the vulnerability of
29 coastal communities in the event of marine flooding and storms. In our study area, we show that maintaining
30 beaches and dunes, by avoiding coastal squeeze, is a valuable preventive measure that is likely to reduce the need

1 for expensive engineering works in some locations (Spalding et al. 2014). However, it is not common practice for
2 public services, coastal managers and engineering companies to incorporate ecosystem services in the economic
3 valuation framework. A stepwise knowledge-sharing process should be set up before the integration of ecosystem
4 services in the policy decision-making framework can be envisaged. Further research should also be conducted to
5 improve our understanding of the impact of SLR on coastal ecosystems (groundwater, beaches and dunes, lagoons
6 and wetlands) and to develop ecosystem-based adaptation strategies.

7

8 **5.3 An introduction to foresight approaches**

9 The four adaptation scenarios considered in this article are theoretical. We consider that the implementation of
10 adaptation options is uniform along the regional coastline. However, in practice, adaptation is place- and context-
11 specific (Field et al. 2014): adaptation options are likely to consist of a spatial and temporal policy mix. Our
12 narrative scenarios and the principal quantitative results of the economic impact analysis were used to introduce a
13 1-day foresight workshop held in June 2012, entitled “*What coastline for the 2010-2050 Languedoc-Roussillon?*”
14 (Montpellier, France). The workshop was organised by the regional authorities and brought together 105 regional
15 experts and stakeholders. Participants were organised into three groups and were asked to adapt and combine
16 various options in order to build plausible adaptation pathways at the regional scale. The resulting scenarios
17 involved two types of combination of “*Laissez-faire*” and Retreat scenarios: (i) the “organised *Laissez-faire*” or
18 “voluntary Retreat” implements both options simultaneously; and (ii) the “two-step Retreat”, which implements
19 the “*Laissez-faire*” scenario first and then the Retreat scenario, as a way to make the Retreat scenario more
20 acceptable. The same approach could be implemented locally (in groups of municipalities). This would probably
21 lead to different combinations of approaches, which would depend on the local environmental, as well as the
22 economic and social contexts, not to mention the outcomes of negotiations and compromise solutions.

23

24 **5. CONCLUSION**

25 Major land-use changes are expected due to SLR at the 2100 time horizon: relocation or densification of urban
26 areas, loss of agricultural land, increase in lagoon areas and modification of wetlands (losses, migration or
27 extension). The total benefit of public adaptation options that are planned in advance could reach €31.2 billion,
28 i.e. €69,000 per inhabitant of the study area in 2010 or €135 million/km of coastline. This valuation is obviously
29 not exhaustive (many ecosystem services and damage to infrastructure are not valued). Therefore, our results
30 should be considered as lower bound estimates. Our findings highlight the importance of (i) raising awareness to

1 ensure that public services and coastal managers can anticipate the consequences of SLR and (ii) incorporating
2 coastal ecosystems into the assessment of the adaptation options. They may be used as an aid for participatory
3 foresight approaches. They could help public services and coastal managers anticipate and plan proactively for
4 SLR: by identifying the ecosystems, coastal populations, infrastructure, agriculture and water resources that should
5 be relocated due to the impacts of SLR; by identifying potential future conflicts among municipalities (for instance
6 caused by the decrease in the availability and/or supply of land and water resources); and by raising awareness of
7 the impacts of SLR on coastal natural habitats and municipalities. Further research is required to develop legal,
8 governance and economic tools that could be used to implement adaptation. An analysis of the feasibility and
9 acceptability of the different options for the local population and decision-makers is also essential.

10

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16

17

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- 1 Electronic supplementary material
- 2 **ESM_1.** Details on the valuation functions per module
- 3 **ESM_2.** Schematic representation of the four adaptation scenarios for the coastal area