National Roadmap for Adaptation 2100

Portuguese Territorial Climate Change Vulnerability Assessment for XXI Century

REPORT

WP5 – Measures and Costs of Adaptation

Final Version

National Roadmap for Adaptation 2100
Portuguese Territorial Climate Change Vulnerability Assessment for XXI Century

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Title: RNA2100 – Measures and Costs of Adaptation

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April 2024

This report is a product of the National Roadmap for Adaptation 2100 project.

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Executive Summary

In the last decade, the global consensus on the urgent need for climate action has increased significantly, as society recognizes climate change as an undeniable threat to humanity. The perils span across the social, economic, and environmental dimensions, affecting human health, security, economic sectors, and ecosystems. The interconnected nature of these impacts underscores the urgency of climate action, requiring immediate efforts in both mitigation and adaptation, involving stakeholders and decision-makers across governmental, corporate, and individual levels. The demand for high-quality climate information has sharply risen at global, regional, and local levels.

Even considering a drastic reduction in greenhouse gas (GHG) emissions towards the end of the 21st century, the impacts of climate change will continue to be felt for decades to centuries. Adaptation becomes crucial for continuous adjustment to expected effects, complementing mitigation and preventing widespread damage. Ongoing assessments, monitoring, updating and improving the available information are essential, engaging public and private entities, decision-makers, and non-governmental organisations.

This report aims to outline the broad priority sectoral adaptation measures, in articulation with the results from the dynamic impact modelling (WP4) and estimate the associated costs and benefits. Stakeholder inputs (WP1) form the basis for this exercise, fostering a comprehensive approach to climate resilience, to inform effective adaptation strategies and promote a more resilient future for Portugal.

Hydrological Balance & Agroforestry

The water resource sector investigated the costs of inaction and the measures taken to adapt to climate change projections. Specifically, the costs of inaction are assessed in the water resources and agroforestry sector, considering factors such as the average cost of water and alterations in water availability and the productivity of the most representative crops across different river basin districts. Additionally, the study explores adaptation measures, with a focus on four strategies studied.

The initial adaptation measur**e** centres on the selection of crops better suited to climate change projections, employing a strategic approach to ensure agricultural resilience and sustainability within evolving environmental conditions, such as temperature increases and the higher likelihood of extreme weather events.

In assessing the advantages of this adaptive measure, the study estimated improvements in water availability and productivity by replacing corn with sunflower crops. Notably, the transition to sunflower cultivation revealed a reduced water requirement over time, coupled with higher yields than corn.

To calculate the associated costs of implementing this measure, detailed information regarding the expenses related to sunflower and corn cultivation was acquired. The divergence in these costs in regions where corn is currently cultivated was then calculated. This comprehensive analysis enabled an estimation of the costs linked to the substitution of crops, revealing the economic viability of transitioning from corn to sunflower cultivation, particularly in the context of adapting to climate change.

The second adaptive measure, focusing on enhancing irrigation efficiency, aims to reduce water consumption in agriculture. Within this project, an examination of water availability results was conducted through the conversion of irrigation systems to drip irrigation, particularly in contexts where it is applicable, such as in corn and vegetable cultivation.

The results demonstrated that the transition from conventional irrigation systems to a more efficient system led to a reduction in water consumption by crops. This is attributed to the direct delivery of water to the plant roots, minimising wastage.

To assess the economic costs of implementing this measure, information on the average cost for the implementation of the drip irrigation system was obtained. The results of this analysis emphasised the viability and cost-effectiveness of replacing irrigation systems, particularly in terms of reducing water consumption.

The third measure implemented in this study involved Reducing system water loss and leakages. The SWAT+ model does not account for water losses and leaks in the water supply system. To address this, information from simulated historical modelling results was utilised to estimate the benefits of reducing losses in the agricultural water distribution network.

Specifically, the losses in the irrigation component, as derived from the simulated historical data, were incorporated, leading to the recalculation of the WEI+. Notably, the results indicated an increase in the water stress index upon the implementation of these losses. This underscores the significance of reducing losses as essential for enhancing water availability over time.

The final measure involves water recycling and reuse, promoting a more sustainable approach to water management across various purposes. In quantifying the advantages of water recycling and reuse, the analysis took into account the hydro-agricultural developments (AH) within each river basin district, along with the wastewater treatment plants situated in those regions. Approximately 80% of the municipal water supply, derived from available wastewater for recycling, resulted in a significant increase in the WEI+, thereby reflecting an augmentation in water availability in the respective regions.

In calculating the costs associated with Reducing system water loss and leakages and Water recycling and reuse, there were observed increases in water use for irrigation compared to the scenario without adaptation. This has the potential to contribute significantly to mitigating the impacts of climate change.

Finally, other measures were considered as a result of the workshops held and other interactions with institutions with decision-making power in agroforestry and water resources making a group of possibilities for adaptation in the context of climate change.

Forest Fires

This study underscores the significance of meteorological variables in developing effective wildfire adaptation measures. Focusing on Fire Radiative Power (FRP) as a key metric, three distinct fire prevention strategies are evaluated, employing varying degrees of randomness and stringency in reducing FRP values associated with Fire Weather Index (FWI) conditions. These strategies are rigorously assessed across historical simulations and future projections, revealing their impacts on mitigating the probability of extreme fire events.

Three key strategies are analysed:

- Strategy 1 – Awareness: Randomly reduces 50% of FRPs associated with FWI values exceeding the sample median. Shows promise in reducing fire occurrences in moderate conditions but demands substantial resources for widespread implementation.
- Strategy 2 – Awareness + Coercive: Varies reduction percentage based on FWI percentiles. Demonstrates a notable impact on reducing fires in regions facing extreme fire weather conditions.
- Strategy 3 – Coercive: Randomly reduces 95% of FRPs in very high FWI conditions. Effectively addresses extremely intense fires during critical fire weather, necessitating focused resources.

Strategy 2 exhibits higher impacts, notably reducing the probability of exceeding log10(FRP) across various energy thresholds. Impact magnitudes increase, particularly for Strategy 2, under severe emission scenarios (RCP 4.5 and RCP 8.5). Strategy 3 proves most sensitive to mitigation scenarios, showcasing significant reductions in wildfires, particularly under high-emission scenarios.

Hence, the following recommendations for stakeholders are listed:

- Recognize Strategy 3 Effectiveness: Acknowledge the efficacy of Strategy 3 in addressing challenges posed by extreme fire weather events, offering a proactive and adaptive approach.

- Prioritise Long-Term Implementation (Strategy 1): Emphasise long-term efforts in implementing Strategy 1 measures, recognizing the challenges associated with changing population mentality and geography.
- Consider Complexities of Strategy 2: Acknowledge the potential complexities of Strategy 2 implementation, requiring a sophisticated infrastructure of warning systems and resources.

In conclusion, this study evaluates three fire prevention strategies, with Strategy 3 emerging as a promising approach for addressing challenges posed by extreme fire weather events. While Strategy 2 shows higher impacts, its implementation complexity may pose challenges. Recommendations provided aim to inform stakeholders and policymakers, offering valuable insights for decision-making in wildfire management and climate resilience. The study recognizes limitations, urging cautious interpretation of results, especially regarding assumptions about static vegetation in future projections. Additionally, adaptation measures linked to concrete strategies underscore the importance of informed, collaborative efforts in addressing evolving wildfire risks.

These strategies may have a positive impact on the losses caused by wildfires, with results pointing to halve the losses if Strategy 2 is implemented. This is particularly important in regions where losses from wildfires are large, such as the central and northern regions of Portugal.

Coastal Areas

Rising sea levels, together with the effects of tides, storm surges and extreme waves are considered key drivers of coastal hazards, threatening coastal infrastructures, ecosystems, and communities. The increase in human pressure along the Portuguese coastlines calls for a reliable, long-term coastal vulnerability assessment, paramount for effective coastal management, sustainable development, adaptation, and impact mitigation strategies, strategically defined to withstand changes until 2100 and beyond. Approximately 30% of the Portuguese coastline has been altered by urban settling, harbour and industrial facilities, and tourism infrastructures, accommodating approximately 75% of the population. In Portugal, the coastal strip up to 50 m inland belongs to the State, and any private parcel within this domain has a public and administrative easement, according to Decree-Law nº 54/2005, modified by Decree-Law nº 78/2013 and Decree-Law nº 34/2014. Therefore, its management and protection policies are the responsibility of State coastal authorities.

In light of the WP4.5/6 dynamic modelling report and the WP1 stakeholder engagement report, the WP5 report on Measures and Costs of Adaptationfor the Portuguese coastal areas focuses on the translation of the physical projected impacts and the expert knowledge of technicians and decision-makers on coastal vulnerabilities to delve into the adaptation measures better suited to deal with the impacts of future climate change. The report is divided into three major sections: the first, focuses on the inaction costs (*i.e.,* the total economic costs in a scenario of no action towards 2100), the second, provides a thorough description of adaptation strategies and measures currently in place and to be applied in the future along the Portuguese coastline, considering the modelling results and the stakeholders' views, and the third, revealing the economic costs associated to the adaptation measures proposed in the previous section (also establishing the cost-benefit between inaction and adaptation costs).

On a first approach, the inaction costs were estimated by crossing the Coastal Vulnerability Index (CVI) cartography (the reader is referred to the WP4.5/6 report) with the geographical distribution of patrimonial value related to the buildings and land projected to become vulnerable, using data from the CENSOS2021, the Portuguese Tax Authority ("*Autoridade Tributária*") and reference values from Ordinances and Decrees-Law. The sum of the vulnerable patrimonial values, at a national scale, under the three CVI levels, corresponds to the overall inaction costs, probabilistically estimated for the range of possible future extreme coastal flooding projections, with a direct relationship with the 100-year (low), 25-year (medium) and 4-year (high) total water level (plus extreme waves for the ocean-facing coastlines) return periods.

A thorough analysis of the current legislation and territorial management instruments in place in Portugal, regarding adaptation measures was undertaken, highlighting the fragilities of the current systems and proposing new measures to deal with the impacts of climate change. From expert knowledge and contact with stakeholders, ten adaptation measures were considered in the WP5 report for the coastal areas. These are (the first five are ordered considering the relative importance highlighted by the stakeholders):

- (1) Artificial beach nourishment;
- (2) Definition of safeguard zones and relocation;
- (3) Rehabilitation of dunes and use of nature-based solutions;
- (4) Cliffs stabilization;
- (5) Maintenance and construction of groins, breakwaters, barriers and dykes;
- Revision of legislation related to IGTs, along with its enforcement to safeguard the infrastructure, communities, and ecosystems in coastal areas;
- Accommodation of urban coastal areas and harbor infrastructure;
- Relocation/removal of structures exposed to risk;
- Incremental and adjustable implementation of a variety of adaptation measures (i.e., from accommodation to relocation);
- Declaration of the Portuguese littoral as a climate emergency zone.

Considering the five key locations in detail (Ofir, Costa Nova, Cova Gala, Costa de Caparica and Praia de Faro), specific adaptation measures were proposed, focusing on the particular characteristics of each area. At Ofir, the most relevant adaptation measures were considered to be artificial beach nourishment and the rehabilitation of dunes and the use of nature-based solutions. These were also considered crucial for Costa da Caparica. At Costa Nova and Gova Gala, artificial beach nourishment was considered a priority, above all the remaining measures. Finally, at Praia de Faro, relocation and removal of structures exposed to risk were considered crucial, along with the rehabilitation of dunes and the use of nature-based solutions. Regarding the existing adherent structures, such as seawalls, accommodation options should be considered along all key locations. The required heights for the coastal protection structures to withstand the future projected extreme coastal events (including a measure of uncertainty, also useful to deal with the statistical possibility of severer events) were shown to be set at 10.64 m (Ofir), 9.46 m (Costa Nova), 7.61 m (Cova Gala), 8.87 m (Costa da Caparica) and 7.77 m (Praia de Faro).

Finally, the adaptation costs were considered, at a national level. These included the costs related to the maintenance of pre-existing structures along the Portuguese coastline, to new planned interventions (such as artificial beach nourishments, considering the projected changes in longshore sediment transport), and to the accommodation of harbor and adherent structures, to include new levels of protection. Finally, the comparison of the adaptation costs with the inaction (“no-action”) ones allowed us to perform a cost-benefit evaluation of the considered strategies. The balance between inaction and adaptation costs allowed us to conclude that generally the cost-benefit ratio of adaptation is low at a national scale, and therefore, adaptation should be pursued. Nevertheless, in very densely urbanized coastal fronts, the adaptation costs related to the accommodation of pre-existing adherent structures or even the remaining infrastructures may saturate the cost-benefit ratio sooner than in the remaining coastal environments, and relocation is suggested in shorter timeframes, ideally to start within the next 20 to 30 years. Specific economic analyses, conducted locally, are recommended, since indirect costs from tourism and local economic activities (unconsidered in the present analysis) may contribute to different adaptation cost-benefit ratios.

1. Introduction

The United Nations Framework Convention on Climate Change came into force in 1994, aiming to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". This level should be achieved over a sufficient period of time to allow ecosystems to adapt naturally to climate change and to ensure that food production is not threatened, allowing sustainable economic development.

The Kyoto Protocol, approved in 1997, came into force in 2005 and established targets for the mitigation of climate change in 192 countries, representing a projected global reduction in the emissions of a set of six greenhouse gases in 5.2%, compared to the levels recorded in 1990. Ten years later, in 2015, the international community present at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21) established that global warming should remain below 2°C compared to the average temperature in the pre-industrial period. This limit was settled to avoid large-scale irreversible changes, and hence, the most serious risks related to climate change. The Paris Agreement (PA), signed by 175 countries, including Portugal, on April 22nd, 2016 (entering into force on November 4th, 2016), seeks to strengthen the implementation of the COP21 guidelines, as well as the global response to the threat of climate change in the context of sustainable development and efforts to eradicate poverty.

Even considering all these efforts, it is clear that mitigation alone is not enough to effectively and unequivocally deal with climate change. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (AR5; IPCC, 2014) concluded that the mean global surface temperature change will most likely exceed 1.5ºC by the end of the 21st century, compared to the pre-industrial period. Such a conclusion leaves the 2ºC threshold enforced by the PA seriously threatened, posing serious consequences for natural and human systems.

Even considering a drastic reduction in greenhouse gas (GHG) emissions towards the end of the 21st century, the concentration of these gases in the atmosphere will not decrease instantly, and climate change will continue to be felt through its physical and socioeconomic impacts, for decades to centuries. Adaptation is therefore essential, in a process of continuous adjustment to the expected effects of climate change (IPCC, 2014), complementing the mitigation component and avoiding damage on a wider scale. Feyen and Watkiss (2011) proposed a practical example to highlight the benefits of timely adaptation to flood risk, concluding that each euro of investment today (in flood protection measures) would avoid the spending of approximately 6 euros on damage costs (EEA, 2017b).

While evidence indicates that human interference with the climate system is indeed occurring on a global scale, the disproportionate impacts of extreme events are felt mainly at the local level. The impacts of recent extreme events, such as heatwaves, droughts, floods and forest fires, demonstrate the significant vulnerability and exposure of some ecosystems and many human systems to (both natural and anthropogenic-driven) climate variability. In Europe, these extreme events have already caused relevant impacts on multiple economic sectors as well as adverse effects on society and health (IPCC, 2014). Portugal is one of the European countries showing the greatest vulnerability to the impacts of climate change. Most recent scientific studies describe southern Europe as a climate change “hotspot”, considering the combined effects of the projected increase in extreme temperatures and decrease in precipitation (Lionello et al., 2014; Turco et al., 2015; Soares et al., 2015; Soares et al., 2017; Cardoso et al., 2019), thus providing an optimal baseline for successful climate change adaptation strategies. Therefore, it is essential for climate change adaptation to be carried out at multiple levels, articulating efforts from the global to the national, regional and local scales, carefully targeting adaptation measures to respond to current vulnerabilities and anticipate future ones (in the medium and long term).

For this reason, a continuous assessment is required to monitor, update, and improve the available information, and foster the involvement of sectoral public and private entities, decision-makers and non-governmental organizations. This process, of a cyclical nature, should be restarted whenever global and/or regional climate scenarios and projections are updated, or when new data and knowledge about impacts, adaptation measures, and social, economic or environmental situations emerge. Subsequently, it has been shown that the need for high-quality climate information has been increasing exponentially (Giorgi et al., 2009; Lemos et al., 2012; Hewitt et al., 2017).

Within this context, in 2007, the European Commission launched the Green Paper on "Adapting to Climate Change in Europe", initiating a process of broad consultation which, together with processes of research and expansion of knowledge, led to the launch of the White Paper "Adapting to Climate Change: Towards a European Framework for Action", in 2009. The main objective of this publication is to establish a framework for reducing the vulnerability of the European Union to the impacts of climate change (COM, 2009). The "European Union Strategy on Adaptation to Climate Change", adopted in 2013, defines a framework and mechanisms to enable the European Union to be prepared to deal with current and future climate-related impacts (COM, 2013). At a national level, Portugal has the National Strategy for Adaptation to Climate Change (ENAAC) since 2010. Its approval, by the Resolution of the Council of Ministers no. 24/2010, of March 18th, placed Portugal among the 17 European countries that, at the time, indicated the availability of an officially approved climate change adaptation strategy.

Overall, Portuguese economic losses caused by climate extremes between 1980 and 2013 amounted to 6783 million euros, of which only 4% was covered by insurance, in contrast to 33% of the European average (EEA, 2017a). While recent estimations point to 60-140 million euros in annual costs associated with forest fires, the 2004/2005 and 2011/2012 droughts had estimated costs of approximately 290 million euros and 200 million euros, respectively.

The most recent climate projections for Portugal, investigated within this project in the Working Package (WP) 2 (Lima et al., 2023a; 2023b), point to a worsening of the (already observed) warming and drying conditions throughout the entire country, although especially in the interior regions. Along the coastlines, while projections point to lower-magnitude atmospheric extremes, the rising sea levels, associated with enhanced erosive trends pose serious threats to future habitability conditions in almost all the urbanized littoral. As the urgent call for climate action increases exponentially, the joint efforts of mitigation and adaptation measures, the participation of all stake-holding and decision-making chain spheres, ranging from government to regional and local authorities, micro- to macro-corporates, and individual behaviour and awareness are essential (Adams et al., 2015; Hallegatte, 2009).

To achieve adaptation on the ground, a comprehensive action plan that outlines the “how”, “when”, and “who” is essential. It is crucial to discover and narrow down viable adaptation possibilities (options) to construct this action plan. Adaptation options seek to address previously identified concerns, resulting from climate change vulnerability and risk assessments. These include taking advantage of any positive opportunities that arise from climate change. Adaptation options can range from actions that build adaptive capacity (*e.g.*, knowledge creation and sharing information, creating supportive institutional frameworks) or establish management systems and supportive mechanisms (*e.g.*, better land management planning, insurance mechanisms) to adaptation actions implemented on the ground, *e.g.*, physical or ecosystem-based measures. Adaptation options vary according to the attitude to risk of those leading the process. Since there is no universal (or fundamentally "correct") answer to the problems associated with climate change, adaptation options (and measures) that offer results by minimizing the risks associated with their implementation, or in other words, through better cost-effectiveness ratios in the face of the uncertainties associated with climate projections, are generally recognized more viable.

Overall, adaptation options are generally presented as:

<u>No-regret:</u> options that are likely to generate socio-economic benefits that exceed their costs, regardless of the magnitude of climate change impacts. It should be noted that even options of this type will always have a cost, however small it may be.

Low or limited regret (low-regret or limited-regret): options for which the associated costs are relatively small, likely to be exceeded by their benefits, considering the uncertainty associated with climate change scenarios. These are directed towards maximizing the return on investment, even for low confidence levels.

Win-win: options that, in addition to serving as a response to climate change, can also contribute with additional social, environmental, and economic benefits.

Flexible/adaptive management: options that involve an incremental (or progressive) strategy, leaving room for more transformative measures, rather than planning adaptation as a single, large-scale action. This approach reduces the risks associated with maladaptation, by introducing concepts that although making sense in the present, are designed to allow for incremental or transformative changes as knowledge, experience and technologies evolve.

Adaptation options are characterized according to the type of actions they promote. The options are often classified according to three categories presented by the European Commission in the White Paper (EC, 2009) and in the European Strategy (EC, 2013), namely:

Grey infrastructure: corresponding to physical or engineering interventions with the aim of better-preparing buildings and other infrastructure to deal with extreme events. This type of option focuses on the direct impacts of climate change on the infrastructure (*e.g.*, changes in temperature and flooding), and usually aims to control (*e.g.*, dykes) or prevent (*e.g.*, irrigation or air conditioning) the threat.

Green infrastructure: increasing the resilience of ecosystems aiming to (among others) reverse the loss of biodiversity, the degradation of ecosystems and the restoration of water cycles. Such approaches use the functions and services of ecosystems to achieve adaptation solutions that are easier to implement and more cost-effective than grey infrastructure. An example is using the cooling effect generated by trees in densely populated areas as a way of improving prevention against extreme heat events.

Non-structural (or soft) options: corresponding to the design and implementation of policies, strategies and processes, such as the integration of adaptation into territorial and urban planning, dissemination of information, economic incentives to reduce vulnerabilities and raising awareness of adaptation (and maladaptation). These may include economic instruments, research and development, and the creation of institutional frameworks and appropriate social structures.

Within the National Roadmap for Adaptation XXI, several sets of adaptation options are identified, for each of the sectors analysed in the WP4 (Hydrological Balance & Agroforestry, Forest Fires and Sea Level Rise & Coastal Erosion and Storm Surges), that can be operationalized through the implementation of concrete adaptation measures, conveniently monitored over time. The inaction and implementation costs are estimated through partnerships with governmental and non-governmental organizations, to produce a thorough and accurate assessment of their sectoral extension.

2. Methodological approach

According to the Intergovernmental Panel on Climate Change (IPCC), adaptation is a dynamic process aimed at adjusting to current or projected climate conditions and their associated impacts. The primary objectives include mitigating or preventing damage and capitalising on potential opportunities. Human intervention plays a crucial role in facilitating adjustments within natural systems. Anticipated as a means to enhance the resilience of natural, social, and economic systems, adaptation to climate change is pivotal for increasing their capacity to cope with ongoing and future changes (IPCC, 2022).

Within the context of the RNA2100 project, the process of identifying and selecting adaptation measures involves a comprehensive approach. This process is grounded in the outcomes of impact modelling within various sectors, explored in Work Package 4 (WP4), which includes Hydrological Balance & Agroforestry, Forest Fires, Sea Level Rise, and Coastal Erosion & Storm Surges. For detailed insights into the projected impacts of climate change scenarios, specific reports for each sector (WP4.1-4, WP4.3, and WP4.5-6) should be consulted.

The initial set of measures, identified through discussions within the project consortium, primarily consists of actions accepted within the sectors under evaluation. These measures predominantly comprise green or grey structural interventions. The initial set of measures aimed at being diverse enough to encompass both incremental and transformative measures. Incremental measures involve marginal changes over time within existing system parameters, such as reducing water losses in the distribution network, stabilizing cliffs in coastal areas, or enhancing response capacity in wildfire situations. On the other hand, transformative ones fundamentally alter the functioning of a system and may include initiatives like water retention landscapes, relocation in coastal areas, or enhancing vegetation resilience to wildfires (Dilling et al., 2023; Pelling et al., 2015). Further details about this initial set of measures can be found in the Work Package 1 (WP1) report on stakeholder engagement. Subsequently, stakeholders evaluated this set of measures in workshops designed to foster brainstorming and generate new ideas. Key stakeholders, experts, and participants contributed with innovative solutions or improvements to existing measures, as outlined in the report.

Once a robust set of adaptation measures was identified for each sector, the subsequent step involved direct and/or indirect modelling of their effectiveness, costs, and benefits (considering the ones that can be modelled). When direct (dynamic) modelling is deemed viable, the same models prepared for impact modelling are considered, and new simulations are created to assess the effectiveness of each measure. Impact modelling proves crucial in understanding potential outcomes, challenges, and the overall benefits of the proposed structural adaptation measures. By incorporating the most detailed information provided by several public and private, governmental, and non-governmental institutions, the inaction costs (without adaptation), investment costs (with adaptation), and associated economic benefits are estimated.

The final set of adaptation measures resulted not only from the workshops and official collaborations but also from interactions with entities not directly involved in the project, stemming from meetings and consultations with decision-makers and implementation stakeholders/institutions. This comprehensive set of measures, especially those challenging to quantify, such as non-structural ones, emphasises the importance of non-structural adaptation. This approach aims to consider measures beyond physical infrastructure changes, involving policy development, capacity building, or awareness programs.

Overall, there is a growing acceptance of measures with transformative characteristics, with new proposals being made by stakeholders with these features. It is also worth noting that there were suggestions at the strategic level, which are more related to adaptation options than specific measures. Regarding the prioritization of measures, different perspectives were observed depending on the analysed sector. In the case of the Hydrological balance & Agroforestry sectors, the highest-prioritized measures, according to stakeholders, are incremental ones, namely the “Selection of crops better suited to climate change projections”, “Increasing irrigation efficiency” and “Reducing water losses in the distribution network”. The measure “Water retention landscapes”, the only transformative one among the six initially proposed, was ranked last. It's important to note that, in these sectors, all remaining measures proposed by stakeholders are incremental, reaffirming the preference previously identified in other studies for incremental approaches within this sector (Dias et al., 2020). Considering the Sea level rise & Coastal erosion and storm surges sectors, the measure of “Artificial beach nourishment” emerged as the most relevant according to stakeholders, one that is already regularly practised in several Portuguese coastal areas. The second measure, however, exhibited transformative characteristics, as it involves the “Definition of safeguard zones and relocation”. Finally, within the Forest fires sector, the highest-prioritized measure is an incremental one, namely “Enhancing vegetation resilience to fire”, followed by a transformative measure aiming at “Reducing the population's vulnerability to fire”.

Within the RNA2100 project, a systematic and inclusive methodology is employed, integrating sector-specific impact modelling, stakeholder engagement, and rigorous evaluation to develop a robust set of adaptation measures. This multifaceted approach ensures the consideration of both structural and non-structural strategies, highlighting the project's commitment to addressing climate change in Portugal comprehensively.

3. Adaptation strategies

3.1. Hydrological Balance & Agroforestry

The hydrological balance as we know it is threatened by climate change, with projected water changes mainly evaluated as precipitation, evapotranspiration, river runoff and soil moisture alterations, affecting water availability, crop productivity, and irrigation requirements. This translates into new challenges for agriculture and water management policies all around the world, albeit with regional differences (IPCC, 2023).

In the Mediterranean region is warming 20% faster than the rest of the global average and we have already experienced changes in drought and aridity during the last century. Several studies showed a decline in precipitation since the 1960s (Hoerling et al., 2012; Gudmundsson and Seneviratne, 2016; Knutson and Zeng, 2018), although, according to records of soil moisture, higher temperatures and increased atmospheric demand also have played a strong role in driving Mediterranean aridity (Vicente-Serrano et al., 2014).

Projected changes for the Mediterranean include a reduction of precipitation of 10 to 15 % with 2 ºC global warming, and with an increase of 2 ºC to 4 ºC in temperature a reduction of up to 30 % in precipitation is projected. River runoff and low flows are expected to decrease (possibly by 12–15% or more) in most locations due to the reduced precipitation (IPCC 2023) as well as groundwater recharge. Water stress in southern European countries is largely driven by growing demand from agriculture, with a potential water deficit of 28–47% by 2030 (Sebri, 2017). Concomitant with the lack of precipitation and rising temperatures, the region will experience an exacerbation in the number and strength of extreme heat events. In addition to the projected shortening in crop growing season, the impact of higher temperatures on crop phenology will likely reduce crop yields. For cereals, olive groves, fruit trees and vineyards, crop yields are expected to dwindle due to the shortening of the crop growing season in association with higher temperatures. Furthermore, high temperatures will delay flowering or bud break in fruit trees and vineyards due to the lack of cumulative chilling. This will not only affect yields but also crop quality. Additional irrigation will be needed for most crops and rain-fed crops might become unsustainable.

For mainland Portugal, where warming and drying trends are projected to exacerbate under high anthropogenic emission scenarios, soil moisture is not expected to rise even in seasons and scenarios where precipitation is projected to increase, albeit moderately. Moreover, drought intensity, frequency and duration are projected to rise. As for the Mediterranean, growing degree lengths and chilling accumulation are also projected to decrease and impact negatively on crop phenology and yield.

3.1.1. Inaction costs

The agroforestry component in the SWAT+ model was defined using the degree days approach to represent various agricultural practices, including land tillage, fertilisation schemes, and the scheduling of planting and harvesting. This characterization aligns with the agricultural calendar under observed conditions, enabling all operations (e.g., planting, harvesting, ploughing) to depend on climatic factors. This functionality facilitates the automatic adjustment of these calendars in response to different climate change scenarios. All results in climate change scenarios consider this assumption, which, in some studies, is regarded as an adaptation measure, though it involves a reactive adaptation carried out by farmers instead of a proactive strategy for addressing modifications related to climate change.

3.1.2. Water resources

To assess the costs of inaction for the water resources sector it must be considered how water availability is estimated to change in each river basin (Figure 3.1.1). The analysis of the results from the modelling performed in SWAT+ (Olmstead, 2013) shows that at the middle of the century, the projection for the median of the water yield changes across the ensemble of models is positive, for river basins 2 to 6 in RCP2.6 and all river basins (except RH1) at the end of the century. In volume, RH3 and RH4 are the river basins with the highest losses in the middle of the century for both RCP4.5 and RCP8.5. High volume losses are also projected for RH5 in RCP8.5 for this period. It is worth noting that losses are projected for all river basins in RCP4.5 and RCP8.5 for both periods. However, with the slight improvement of the climate at the end of the century in RCP4.5, the losses in this scenario are lower in relation to mid-century. Once again, RH3, RH4 and RH5 are the river basins with the highest volume losses.

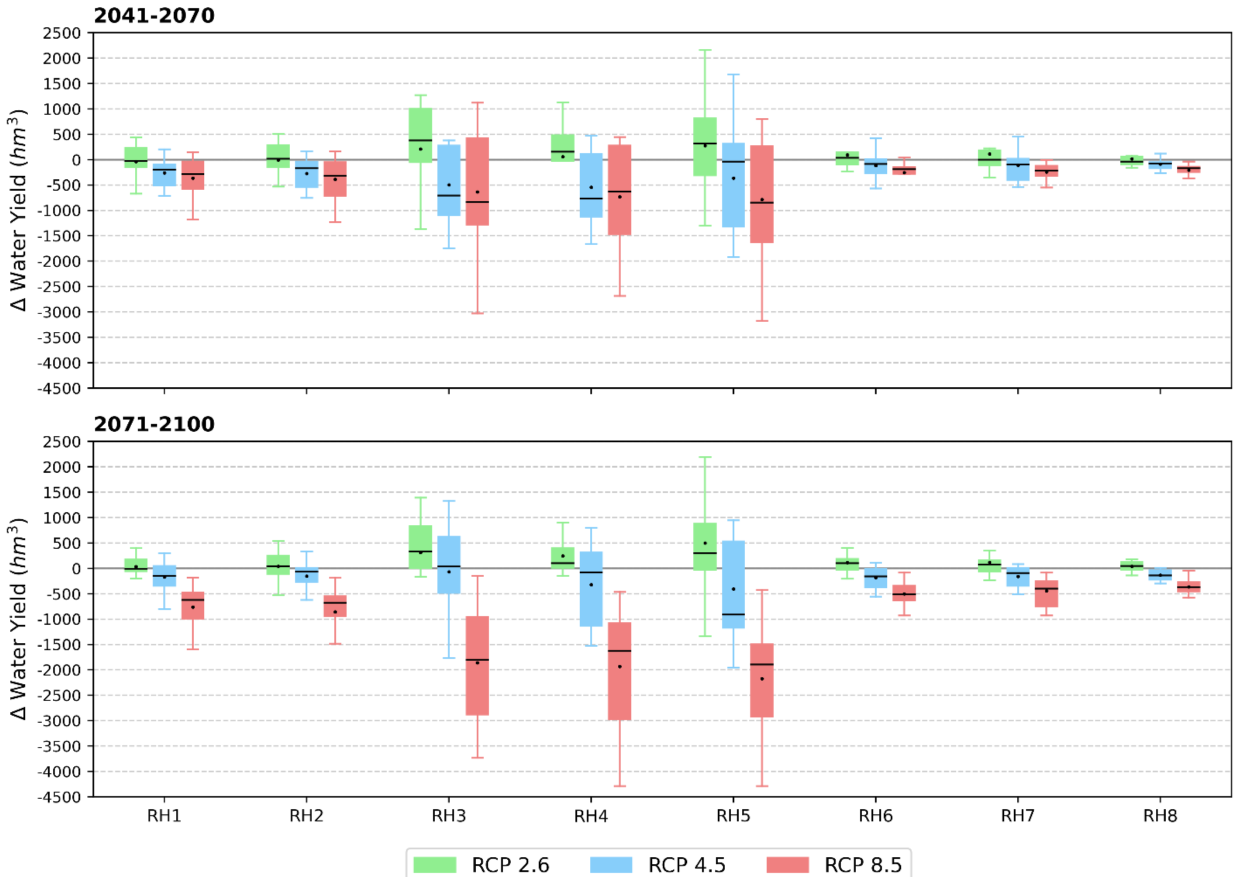


Figure 3.1.1 – Projected changes in averaged water yield (mm) for mainland Portugal river basin districts. Two future periods are shown: 2041-2070, and 2071-2100, under all emission scenarios – RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (red). The boxplots represent the spread across models, with the 10th and 90th percentiles signalled by the whiskers and the distance between the 25th and 75th percentile represented by the box; the black dash is the median and the black dot is the ensemble mean.

To estimate the associated costs to the projected water scarcity, the economic values associated with the average cost of water for each river basin were obtained. The estimated cost of water per river basin district, based on data from APA (2023), can be found in Table 3.1.1.

Table 3.1.1 – Estimated costs of water per river basin, considering different water usage (e.g. agriculture, thermo-and hydroelectrical energy production, public water system, etc.). Water resource rate from APA (2023).

River Basin	Water value €/m^3	River Basin	Water value €/m^3
RH1	0.00037	**RH5**	0.00087
RH2	0.00032	**RH6**	0.0065
RH3	0.0001	**RH7**	0.00354
RH4	0.00094	**RH8**	0.00829

After considering the accumulated water yield changes for every period and scenario and applying the information from Table 3.1.1 the associated changes in costs per river basin can be seen in Table 3.1.2. Considering the median of the water yield changes across the ensemble of models, minor economic gains are projected for river basins district 2 to 6 in RCP2.6 at the middle of the century and for all river basins (except RH1) at the end of the century. Note that although RH6 and RH8 do not have the largest volume loss, the cost of water in these basins implies projected great losses (greater than 1 M€) for the middle of the century in RCP8.5 and RCP4.5, and RCP8.5 at the end of the century. In RCP8.5 and at the end of the century, only the northern river basins (RH1, 2, 3) have losses lower than 1M€ and in RH6 and RH8 the projected losses are greater than 3 M€.

Table 3.1.2 – Projected changes of economic costs in euros (€) due to water yield changes for mainland Portugal river basin districts. Two future periods are shown: 2041-2070, and 2071-2100, under all emission scenarios – RCP2.6, RCP4.5 and RCP8.5. The presented values refer to the ensemble median.

Projected changes of economic costs (€)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
RH1	-8,572	-71,903	-104,804	-2,716	-54,955	-230,210
RH2	6,001	-54,687	-101,046	13,817	-21,080	-216,963
RH3	38,096	-70,489	-83,087	32,788	3,291	-180,156
RH4	148,512	-722,997	-590,293	93,267	-74,812	-1,528,329
RH5	276,879	-32,755	-733,952	261,248	-793,008	-1,647,449
RH6	218,472	-565,057	-1,243,767	665,385	-1,045,925	-3,337,946
RH7	-4,427	-348,192	-764,628	263,288	-317,151	-1,423,224
RH8	-297,557	-628,965	-1,399,258	365,366	-1,141,317	-3,039,448

3.1.3. Agroforestry

The projected climate changes in water availability, resulting in hydrological and agricultural drought in many regions of the Portuguese mainland, will affect the productivity of crops, with associated costs.

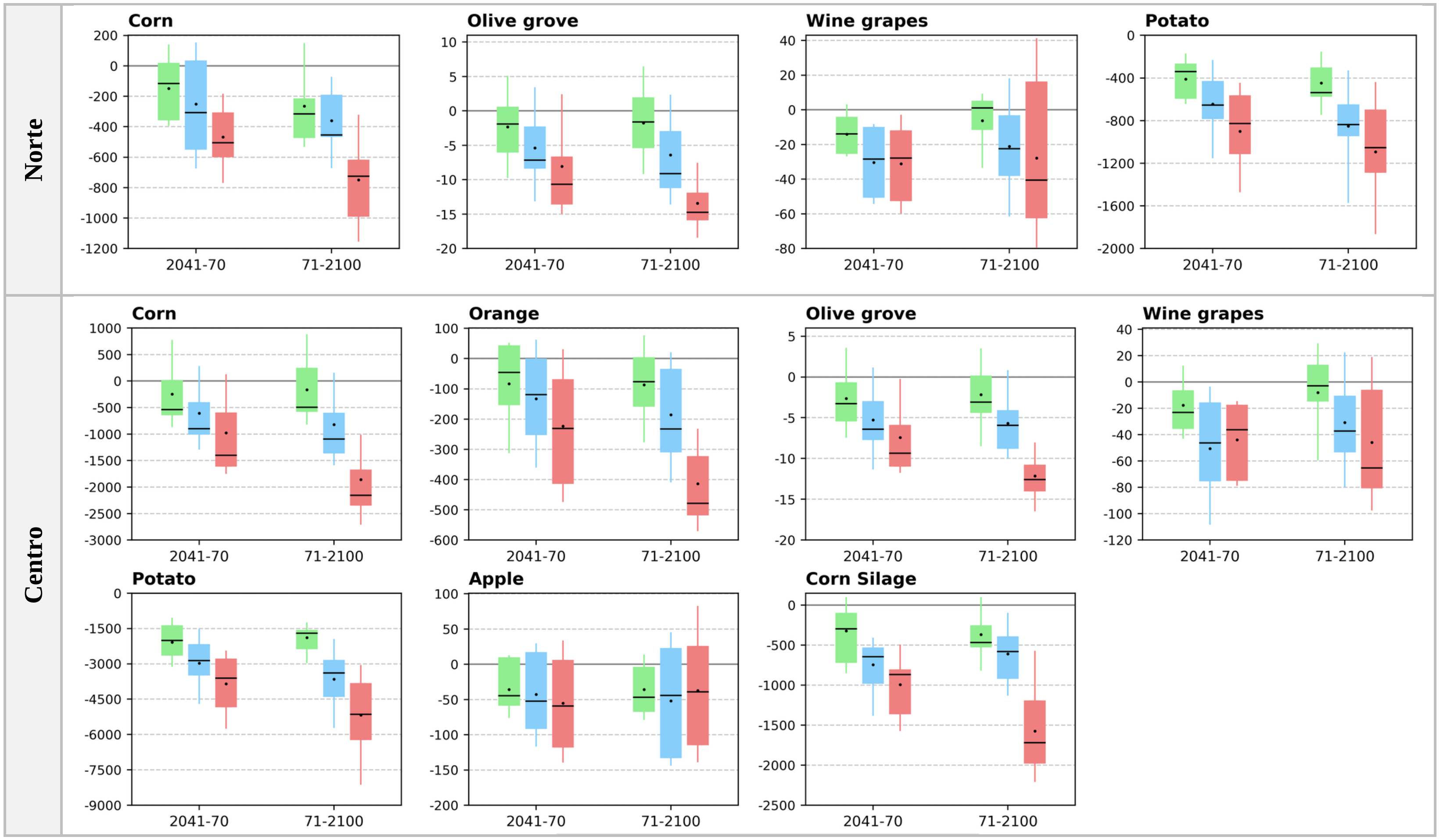
For agroforestry, the costs of inaction were estimated for the two periods under analysis, considering the modifications in the productivity of the most representative crops in each Portuguese NUTS II, resulting from the modelling performed in SWAT+ and EPIC. This approach is dependent on obtaining economic values associated with these crops (€/dry biomass weight), which was possible after applying a crop-dependent factor to convert the crop's weight from dry to fresh biomass, based on Standard EU aggregate humidity (Eurostat, 2024). The Cabinet for Planning, policies, and General Administration (GPP, 2023) publishes periodically a reference table with crop values in the context of insurance for crops. These values, for the year 2023, are the baseline for the agricultural crop productivity costs presented in this report (Table 3.1.3).

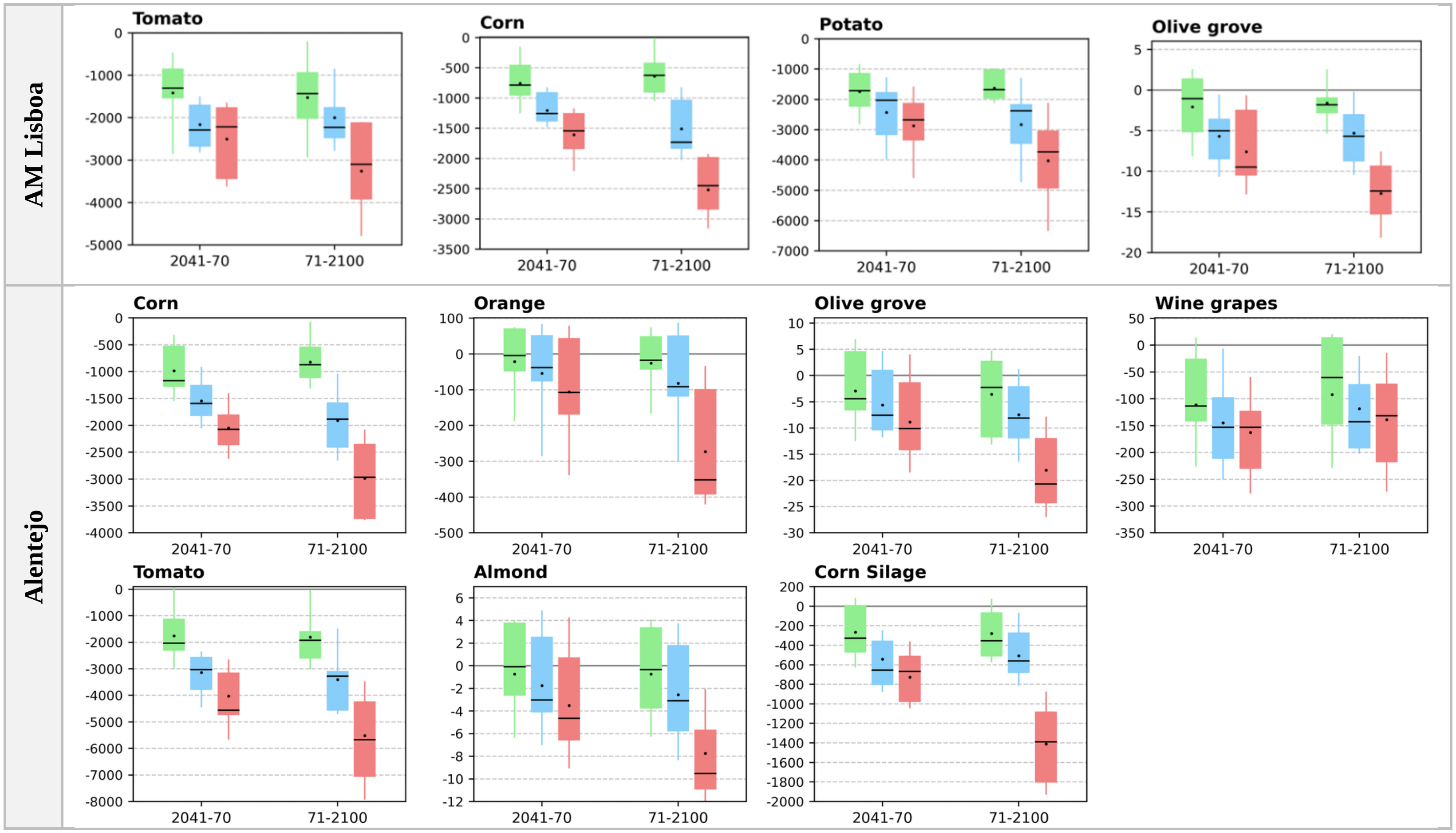
Table 3.1.3 – Insurance values for crops included in the SWAT+ modelling exercise.

Crop	Fresh biomass value (€/Kg)	Crop	Fresh biomass value (€/Kg)
Almond	0,781	Lettuce	0,510
Apple	0,756	Olive grove[1]	0,563
Cabbage[2]	0,509	Orange	0,564
Corn	0,250	Potato[3]	0,388
Corn silage	0,045	Rice	0,393
Grain sorghum	0,110	Strawberry	2,807
Grape	2,077	Tomato	0,145

Figure 3.1.2 synthesizes the projected changes in productivity (kg/ha) for the principal crops developed in each NUTS II of mainland Portugal. The productivity losses assume the continued existence of current irrigation infrastructure in the future, the availability of sufficient water for irrigation, and nutrients for plant growth. These assumptions align with those applied in the PESETA IV project (Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis). In this context, productivity losses and economic losses are related to modifications in climatic conditions for the crops currently developed in the region due to changes in plant phenology. An analysis of the common crops between all NUTS II or in between two NUTS II reveals that productivity within the same crop decreases from North to South following the increase in temperature and decline of precipitation.

[1] Considering the average value for both table olives and olives for olive oil production
[2] Considering the average value for many different types of cabbages consumed in Portugal.
[3] Considering the average value for “Potato conservation, for seed, and Primor”.


Norte
Corn
Olive grove
Wine grapes
Potato
Centro
Corn
Orange
Olive grove
Wine grapes
Potato
Apple
Corn Silage
2041-70
71-2100


AM Lisboa
Alentejo
Tomato
Corn
Potato
Olive grove
Orange
Wine grapes
Almond
Corn Silage
2041-70
71-2100

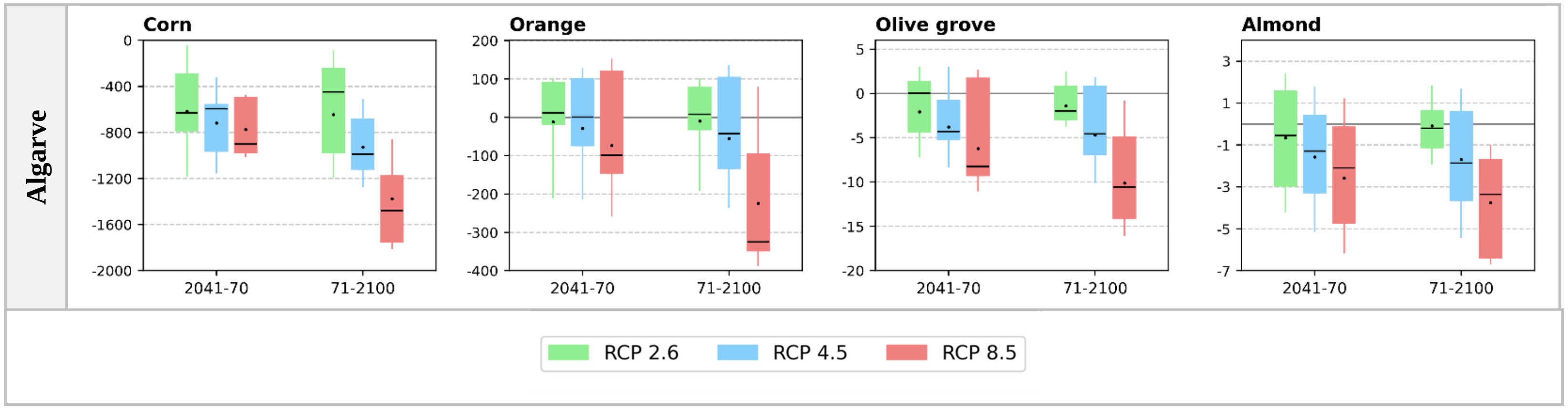


Figure 3.1.2 – Projected changes in productivity (kg/ha) for the main crops developed in each NUTS II of mainland Portugal. Two future periods are shown: 2041-2070 and 2071-2100, under all emission scenarios – RCP2.6 (green), RCP4.5 (blue), and RCP8.5 (red). The boxplots represent the spread across models, with the 10th and 90th percentiles indicated by the whiskers and the interquartile range represented by the box; the black dashed line represents the median, and the black dot represents the ensemble mean.

In general, productivity falls from scenario RCP2.6 to RCP8.5. In line with the constant increase in temperature in scenario RCP8.5, increasing reductions in productivity are projected from mid-century to the end of the century. The improvement of the climatic conditions from mid-century to the end of the 21st century in RCP2.6 stabilises the losses at values near the ones projected for mid-century and it is worth noting that apart from vineyard in Norte and Centro, the productivity never recovers to values like the historical. The stabilisation of CO_2 emissions from mid-century onwards in RCP4.5 has an impact on the escalation of temperature as seen in WP2, however, for most crops the productivity at the end of the century is lower than at mid-century. For all crops, except for orange in the Algarve, the median of the ensemble, in all scenarios and for both periods, indicates a loss in productivity.

A crop which is planted in all NUTS II and in all scenarios with a robust decrease in productivity (> 75% of the models agree on the signal of change), projected in both temporal windows is corn. An exception is observed at the end of the century in RCP2.6 with almost half of the models projecting a limited increase in productivity in relation to mid-century. At the end of the century, and in RCP8.5 the decrease in productivity rages from 1 ton/ha to 3.5 ton/ha. It is worth noting that the loss of biomass is associated with the loss of productivity, indicating that the rise in temperature across the 21st century reduces the ability of the plants to grow/survive since their water needs are always met. Similar robust projections occur for tomato and potato where median losses for all scenarios at the end of the century are between 1.5 and 6 ton/ha for the first and 1 and 5 ton/ha for the latter. The losses of the other crops have the median of the largest loss near 0.5 ton/ha for orange, 150 kg/ha for vineyard, 50 kg/ha for apples, 20 kg/ha for olive grove and 10 kg/ha for almond.

Table 3.1.4 shows the projected changes in economic costs in thousands of euros for the Norte NUTS II for the crops in Figure 3.1.2 (values refer to median productivity). The largest losses are associated with potatoes from -25 M€, -48 M€ to -77 M€ at the end of the century for RCP2.6, 4.5 and 8.5 respectively, followed by corn (-10 M€ to -22 M€) and vineyard (-0.5 M€ to -21 M€). Losses in olive grove are less than -100 k€ to -850 k€. Overall, the agricultural losses in this NUT II range from -33 M€ to -126 M€.

Table 3.1.4 – Projected changes of economic costs in thousand euros (k€) due to crop yield changes for the main crops developed in the Norte NUTS II of mainland Portugal. Two future periods are shown: 2041-2070, and 2071-2100, under all emission scenarios – RCP2.6, RCP4.5 and RCP8.5. The presented values refer to the ensemble median.

Productivity losses (k€) NUTS II Norte	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Corn	-3,589	-9,463	-15,558	-9,738	-13,965	-22,336
Olive Grove	-111	-412	-614	-93	-525	-850
Vineyard	-7,086	-14,443	-14,191	572	-11,381	-20,648
Potato	-27,627	-56,382	-57,302	-25,653	-48,458	-77,091
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Total	**-43,418**	**-75,512**	**-92,217**	**-32,842**	**-75,192**	**-126,250**

Table 3.1.5 shows the projected changes of economic costs in thousands of euros for the Centro NUTS II for the crops in Figure 3.1.2 (values refer to median productivity). Once again, the largest losses are associated with potatoes from -41 M€, -102 M€ to -153 M€ at the end of the century for RCP2.6, 4.5 and 8.5 respectively, followed by corn (-14 M€ to -62 M€) and vineyard (-1 M€ to -21 M€). Although, the changes in apple's productivity are similar between scenarios and climate windows, projected median losses range between -2.5 M€ and -4 M€. Olive Grove's losses are similar to the one in Norte. Overall, the agricultural losses in this NUT II range from -66 M€ to -297 M€.

Table 3.1.5 – Projected changes of economic costs in thousand euros (k€) due to crop yield changes for the main crops developed in the Centro NUT II of mainland Portugal. Two future periods are shown: 2041-2070, and 2071-2100, under all emission scenarios – RCP2.6, RCP4.5 and RCP8.5. The presented values refer to the ensemble median.

Productivity losses (k€) NUT II Centro	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Corn	-15,471	-25,789	-40,281	-14,243	-31,441	-61,904
Orange	-22	-56	-109	-36	-110	-227
Olive Grove	-193	-380	-553	-183	-352	-745
Vineyard	-7,553	-15,142	-11,911	-939	-12,225	-21,438
Potato	-61,731	-102,641	-108,744	-41,105	-102,286	-153,052
Apple	-2,787	-3,267	-3,706	-2,919	-2,763	-2,439
Corn Silage	-54	-119	-160	-86	-107	-316
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Total	**-92,869**	**-153,770**	**-177,240**	**-66,198**	**-183,270**	**-296,700**

Table 3.1.6 shows the projected changes of economic costs in thousands of euros for the AML NUTS II for the crops in Figure 3.1.2 (values refer to median productivity). Once again, the largest losses are associated with potatoes from -5 M€, -8 M€ to -11 M€ at the end of the century for RCP2.6, 4.5 and 8.5 respectively, followed by corn (-3 M€ to -11 M€) and tomato (-2 M€ to -4 M€). Overall, the agricultural losses in this NUT II range from -14 M€ to -41 M€.

Table 3.1.6 – Projected changes of economic costs in thousand euros (k€) due to crop yield changes for the main crops developed in the AML NUT II of mainland Portugal. Two future periods are shown: 2041-2070, and 2071-2100, under all emission scenarios – RCP2.6, RCP4.5 and RCP8.5. The presented values refer to the ensemble median.

Productivity losses (k€) NUT II AML	2041-2070			2071-2100		
	RCP2.6	**RCP4.5**	**RCP8.5**	**RCP2.6**	**RCP4.5**	**RCP8.5**
Tomato	-1,660	-2,918	-2,825	-1,825	-2,844	-3,950
Corn	-3,548	-5,686	-6,969	-2,820	-7,818	-11,086
Potato	-5,413	-6,431	-8,475	-5,320	-7,537	-11,814
Olive Grove	-1	-5	-11	-2	-6	-14
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Total	**-17,168**	**-29,706**	**-31,272**	**-14,064**	**-27,633**	**-41,465**

Table 3.1.7 shows the projected changes of economic costs in thousands of euros for the Alentejo NUTS II for the crops in Figure 3.1.2 (values refer to median productivity). The largest losses are associated with corn from -20 M€, -43 M€ to -68 M€ at the end of the century for RCP2.6, 4.5 and 8.5 respectively, followed by vineyard (-15 M€ to -34 M€) and tomato (-7 M€ to -21 M€). In this region, the losses in the olive grove are also substantial, reaching values larger than -1 M€ in both temporal climate windows in RCP4.5 and RCP8.5. In the latter, losses are near -3 M€. Overall, the agricultural losses in this NUT II range from -132 M€ to -182 M€.

Table 3.1.7 – Projected changes of economic costs in thousand euros (k€) due to crop yield changes for the main crops developed in the Alentejo NUT II of mainland Portugal. Two future periods are shown: 2041-2070, and 2071-2100, under all emission scenarios – RCP2.6, RCP4.5 and RCP8.5. The presented values refer to the ensemble median.

Productivity losses (k€) NUT II Alentejo	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Corn	-26,951	-36,722	-47,820	-20,051	-43,451	-68,454
Orange	-9	-73	-208	-34	-177	-679
Olive Grove	-601	-1,032	-1,379	-312	-1,107	-2,817
Vineyard	-27,705	-37,274	-37,318	-14,720	-34,790	-32,095
Tomato	-7,353	-10,965	-16,519	-6,974	-11,866	-20,552
Almond	-0.2	-6	-9	-1	-6	-19
Corn Silage	-227	-453	-462	-246	-388	-961
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Total	**-79,946**	**-58,441**	**-121,010**	**-131,530**	**-131,320**	**-181,680**

In Algarve, (Table 3.1.8), the largest losses are associated with orange from -700 K€ to -10 M€ at the end of the century for 4.5 and 8.5 respectively. For RCP2.5 the median of the ensemble projects some gains around +600 k€. In this region, the individual losses in the other crops are less than 0,5 M€. Overall, the agricultural losses in this NUT II range from -3 M€ to -13 M€.

Table 3.1.8 – Projected changes in economic costs in thousand euros (k€) due to crop yield changes for the main crops developed in the Algarve NUT II of mainland Portugal. Two future periods are shown: 2041-2070, and 2071-2100, under all emission scenarios – RCP2.6, RCP4.5 and RCP8.5. The presented values refer to the ensemble median.

Productivity losses (k€) NUTS II Algarve	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Orange	+498	+315	-2,070	+571	-657	-9,772
Almond	-5	-11	-18	-1	-16	-30
Corn	-230	-218	-309	-155	-356	-534
Olive Grove	0	-63	-122	-29	-68	-157
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Total	**-1,353**	**-3,293**	**-5,114**	**-2,783**	**-5,625**	**-13,272**

3.1.4. Adaptation measures

Regarding the water resources and agroforestry sectors, four adaptation measures were computed based on SWAT+ results. Those measures consist of: i) Selection of crops better suited to climate change projections; ii) Improved irrigation efficiency; iii) Reducing system water loss and leakages; and iv) Water recycling and reuse (ApR).

Other measures are considered as a result of the workshops held within the scope of WP1, and other interactions with institutions with decision-making power in agroforestry and water resources. The final proposed measures can be grouped into adaptation responses (Table 3.1.9).

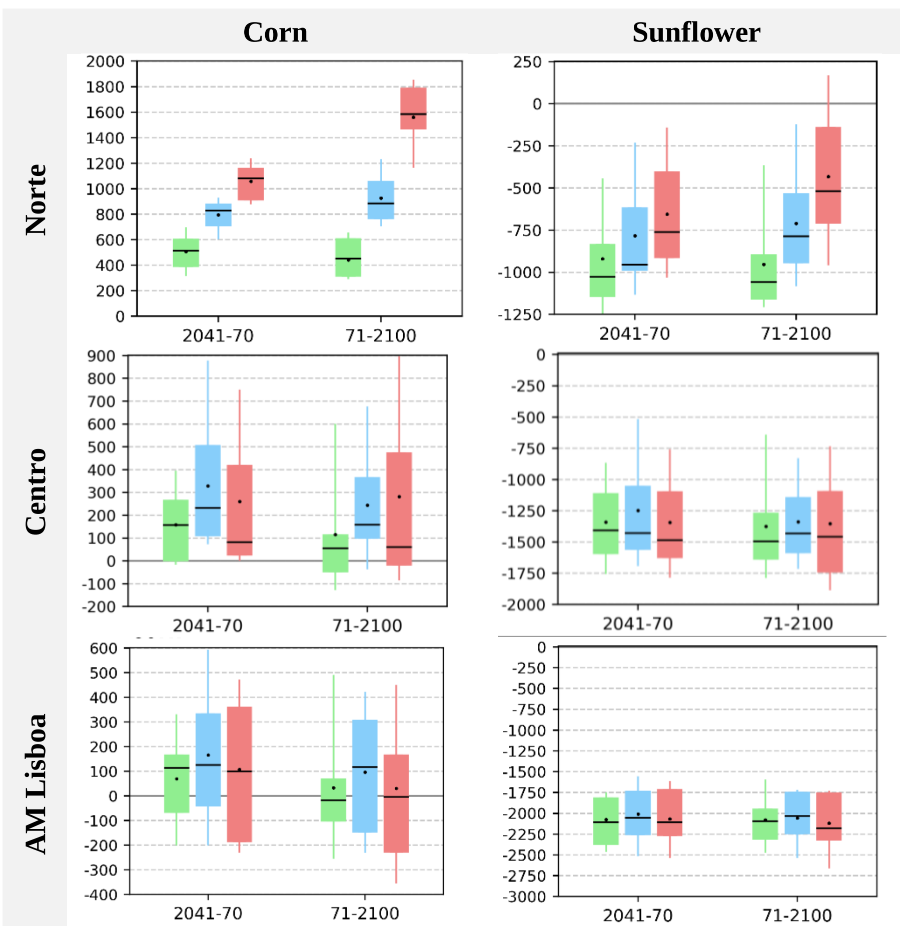
Table 3.1.9 – Adaptation measures proposed for Hydrological Balance & Agroforestry sectors. Bold: measures whose effectiveness and benefits result from modelling. The organisation of the table is based on United Nations Environment, 2017.

Adaptation response 1: Water efficiency and demand management	**Adaptation response 2: Water storage**	**Adaptation response 3: Alternative water sources**
Selection of crops better suited to climate change projections (low regrets) *	Rainwater harvesting for storage (no regrets/win-win)	**Water recycling and reuse** (no regrets) *
Improved irrigation efficiency (no regrets/win-win)	Soil moisture conservation technique (no regrets, low regrets)	Seawater desalination (no regrets)
Reducing system water loss and leakages (no regrets)	Water retention landscapes (no regrets/win-win)	-
Public water conservation campaigns (no regrets, adaptive management)	New reservoirs or connection between existing reservoirs (low regrets)	-
Awareness and training of farmers (no regrets, adaptive management)	-	-
Water metering (no regrets, adaptive management*	-	-
Water licences and permits (no regrets, adaptive management) **	-	-
Progressive pricing (low regrets, adaptive management) **	-	-

The combination of measures is recommended to provide a better adaptation response, namely:
*Selection of crops better suited to climate change projections + Water metering + Water recycling and reuse
**Water licences and permits + Progressive pricing

Measure 1: Selection of crops better suited to climate change projections.

Selecting crops better suited to climate change projections involves a strategic approach to ensure agricultural resilience and sustainability in changing environmental conditions, such as temperature increases and the higher likelihood of extreme weather events. In situations of climatic stress, farmers may select plants with traits such as drought tolerance, and heat resistance, but also resistance to pests and diseases associated with changing climate conditions (Raza et al., 2019). Other key practices may involve adjusting planting schedules (sowing earlier or later in the season) or moving cultivation to areas with more favourable conditions based on climate projections. In this particular context, to evaluate the advantages of such adaptive measures, irrigation needs were estimated by replacing corn cultivation with sunflower in mainland Portugal (Figure 3.1.3).



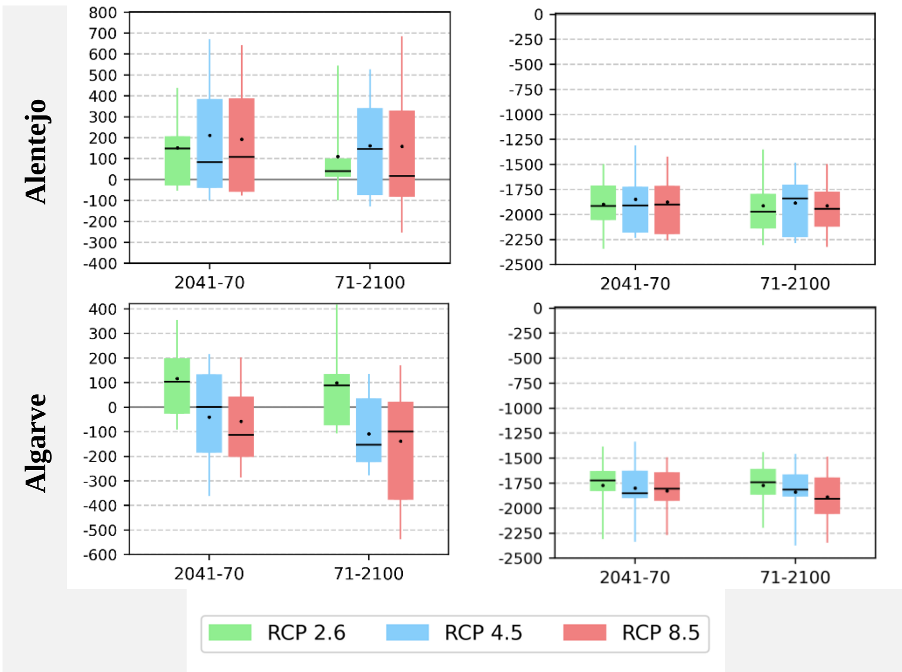


Figure 3.1.3 – Projected changes in irrigation needs (m³/ha) for corn and sunflower crops developed in each NUT II of mainland Portugal. Two future periods are shown: 2041-2070 and 2071-2100, under all emission scenarios – RCP2.6 (green), RCP4.5 (blue), and RCP8.5 (red). The boxplots represent the spread across models, with the 10th and 90th percentiles indicated by the whiskers and the interquartile range represented by the box; the black dashed line represents the median, and the black dot represents the ensemble mean.

As shown in Figure 3.1.3, in general, the increase in corn irrigation needs is projected over the century. In the regions where this does not occur, a considerable decrease in biomass is projected, thus the scenarios have less volume of crop planted. Less crop implies reduced irrigation needs. By replacing corn with sunflower, a widespread decrease in irrigation needs is estimated under all RCP scenarios and periods (Figure 3.1.3). This reduction in irrigation needs by sunflower compared to corn can be attributed to the crop characteristics since in this case a very limited reduction in sunflower's biomass is projected.

The root structure of sunflowers is often more extensive and deeper than corn's, allowing for more effective moisture absorption from the soil. Additionally, the evapotranspiration rate of sunflowers tends to be lower compared to corn. This means that sunflowers lose less water to the atmosphere, conserving more water for their growth and development. Another physiological characteristic of the sunflower refers to the orientation of its flowers toward the sun, which contributes to optimising the use of sunlight, promoting better utilisation of available water.

The characteristics of the sunflower enhance its capacity to adapt to climate change compared to corn, making it a more sustainable option, especially considering the projected decrease in water availability over time. The projected changes in the Water Exploitation Index Plus (WEI+) are in line with this claim (Table 3.1.10). Comparing these results with the WEI+ found in the WP4 report (Table 12), we can identify an improvement of up to 6 pp in RH5 and 12 pp in RH7. Nevertheless, the southern regions of Portugal (RH6, RH7, and RH8) are still expected to reach severe and extreme water scarcity conditions, while the central region (RH5) approaches high water stress. The projection for regions positioned above (RH1, RH2, RH3, and RH4) suggests they remain low or no water stress over the century.

Table 3.1.10 – Projected changes in WEI + (percent points) considering measure 1. Three future periods are shown: 2011-2040, 2041-2070, and 2071-2100, under all emission scenarios – RCP2.6, RCP4.5, and RCP8.5. The presented values refer to the multi-model ensemble median.

River Basin	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
RH1	-0.33 pp	-0.19 pp	-0.02 pp	-0.42 pp	-0.25 pp	+0.23 pp
RH2	-0.60 pp	-0.33 pp	+0.05 pp	-0.73 pp	-0.64 pp	+0.70 pp
RH3	-0.42 pp	+0.20 pp	+0.19 pp	-0.56 pp	-0.09 pp	+1.38 pp
RH4	-0.77 pp	-0.36 pp	-0.36 pp	-1.11 pp	-0.37 pp	+0.97 pp
RH5	-1.57 pp	+0.12 pp	+0.08 pp	-2.02 pp	-0.52 pp	+4.97 pp
RH6	+0.55 pp	+4.05 pp	+10.85 pp	-0.46 pp	+6.09 pp	+45.25 pp
RH7	+1.93 pp	+5.79 pp	+24.93 pp	+0.59 pp	+6.29 pp	+86.65 pp
RH8	+1.41 pp	+3.51 pp	+16.32 pp	-0.63 pp	+4.14 pp	+26.65 pp

Measure 2: Improving irrigation efficiency.

The goal of this measure is to reduce water consumption in agriculture while sustaining high crop productivity. This purpose can involve implementing technologies that enable precise control and monitoring of irrigation processes, such as soil moisture sensors and automatic irrigation scheduling based on weather conditions. In the past decades, the implementation of advanced irrigation systems, such as drip irrigation, has also been promoted as water is delivered directly to the roots of plants, minimising wastage. In this project, water availability results were analysed by converting the irrigation systems to drip irrigation whenever appropriate (such as maize or vegetable cultivation). Changes were made to the irrigation efficiencies according to Table 3.1.11. The reintroduction of irrigation to the system was partially considered.

Table 3.1.11 – Improvements in Irrigation Efficiency for Crops within and outside Hydro-agricultural Development (AH).

Crop	Irrigation System	Irrigation System improvements	Irrigation Efficiency	
			Before	After
Cabbage	Sprinkler	Drip	0.85	0.9
Corn	Sprinkler	Drip	0.85	0.9
Csil	Sprinkler	Drip	0.85	0.9
Lettuce	Sprinkler	Drip	0.85	0.9
Potato	Furrow	Drip	0.7	0.9
Rice	Furrow	Drip	0.7	0.9
Sunflower	Sprinkler	Drip	0.85	0.9

The WEI+ was recalculated to assess water availability over time under all emission scenarios by making use of an efficient drip irrigation system (Table 3.1.12). Changes in the WEI+ for future periods follow the same magnitude as the previous adaptation measure; improvements of around 1pp (up to 5pp) were found in comparison to the current irrigation systems implemented in the study areas.

Table 3.1.12 – Projected changes in WEI + (percent points) considering measure 2. Three future periods are shown: 2011-2040, 2041-2070, and 2071-2100, under all emission scenarios – RCP2.6, RCP4.5, and RCP8.5. The presented values refer to the multi-model ensemble median.

River Basin	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
RH1	+0.11 pp	+0.33 pp	+0.49 pp	+0.07 pp	+0.40 pp	+1.41 pp
RH2	+0.13 pp	+0.72 pp	+0.99 pp	+0.02 pp	+0.71 pp	+3.43 pp
RH3	-0.22 pp	+0.36 pp	+0.40 pp	-0.13 pp	+0.22 pp	+2.01 pp
RH4	+0.05 pp	+0.67 pp	+0.54 pp	-0.37 pp	+0.27 pp	+2.46 pp
RH5	-0.39 pp	+0.98 pp	+0.90 pp	-0.95 pp	+0.94 pp	+8.22 pp
RH6	+0.03 pp	+3.74 pp	+8.29 pp	-0.96 pp	+4.43 pp	+43.59 pp
RH7	+2.78 pp	+9.36 pp	+30.40 pp	+0.99 pp	+6.91 pp	+89.53 pp
RH8	+1.41 pp	+3.52 pp	+16.27 pp	-0.64 pp	+4.11 pp	+26.59 pp

Measure 3: Reducing system water loss and leakages.

Non-revenue water (i.e., water that is produced and lost before reaching the customer) results in a financial and environmental burden for water utilities. This measure aims to increase distribution system efficiency and prevent needless withdrawals. By adopting a combination of advanced technologies (such as sensors and satellite-based monitoring systems), pressure management (optimising water pressure within the distribution system to reduce stress on pipes), upgrading infrastructure (replacement or rehabilitation of ageing and deteriorating pipes), engaging consumers (raise awareness about water conservation and the importance of reporting leaks promptly), and implementing policy measures (financial penalties for excessive losses and rewards for meeting reduction targets), water utilities can markedly reduce system water loss and leakage (United Nations Environment, 2017).

The SWAT+ model does not account for water losses and leaks in the water supply system. Results from modelling simulations presented in the WP4 report were then assumed to estimate the benefits of reducing losses in the agricultural water distribution network.

Based on this limitation and to estimate the benefits of reducing losses in the agricultural water distribution network, the WEI+ was recalculated considering the irrigation component obtained from modelling simulations and the information from the efficiency of the Hydro-agricultural developments (Table 3.1.13). The return of the agricultural water losses in the distribution network to the system was not considered.

Table 3.1.13 – Efficiency in distribution network available for Hydro-agricultural development.

Hydro-agricultural Development	Water supply system	Efficiency in distribution	Water origins (reservoirs)
Luz	Under pressure	79,2	Alqueva
EFMA	-	95	Alqueva
			Pedrógão
Alto Sado	By gravity	85	Monte da Rocha
Alvor	By gravity	75	Bravura
Baixo Mondego	Under natural or induced pressure	71,3	Aguieira
Caia	Under pressure and by gravity	80	Caia
Campilhas	By gravity	85	Campilhas
Idanha-a-Nova	By gravity	60	Idanha
Cova da Beira	Under pressure	79,2	Meimoa
			Sabugal
Divor	By gravity	60	Divor
Fonte Serne	By gravity	65,5	Fonte Serne
Lucefecit	Under pressure and by gravity	61,3	Lucefecit
Macedo de Cavaleiros	Under pressure	69,2	Azibo
Minutos	Under pressure	89,2	Minutos
Mira	By gravity	65	Santa Clara

Hydro-agricultural Development	Water supply system	Efficiency in distribution	Water origins (reservoirs)
Monte Gato e Migueis	By gravity	100	Monte Gato; Miguéis
Odivelas	Under pressure and by gravity	80	Odivelas
Roxo	Under pressure and by gravity	90	Roxo
Silves, Lagoa e Portimão	By gravity	70	Arade
Sotavento Algarvio	By gravity	91	Odeleite-Beliche
Vale do Sado	By gravity	70	Pego do Altar
			Vale do Gaio
Vale do Sorraia	By gravity	74,5	Montargil
			Maranhão
Vigia	Under pressure	69,2	Vigia

When comparing the projected changes for WEI+ from WP4 (Table 12) (meaning no water losses) and Table 3.1.14 (with water losses), we can identify an improvement of around 2 pp (up to 9 pp) when reducing non-revenue water. These findings suggest the changes over the century in water stress categories described in the WP4 report remain valid for this adaptation measure. Nevertheless, please notice that the dimensions of the studied areas (presented here as river basin districts) smooth the results, buffering the impacts on a smaller scale.

Table 3.1.14 – Projected changes in WEI+ (percent points) considering measure 3. Three future periods are shown: 2011-2040, 2041-2070, and 2071-2100, under all emission scenarios – RCP2.6, RCP4.5, and RCP8.5. The presented values refer to the multi-model ensemble mean.

River Basin	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
RH1	+0.35 pp	+0.70 pp	+0.81 pp	+0.25 pp	+0.56 pp	+1.68 pp
RH2	+0.58 pp	+1.31 pp	+1.43 pp	+0.45 pp	+0.95 pp	+3.99 pp
RH3	+0.05 pp	+0.47 pp	+0.52 pp	+0.04 pp	+0.45 pp	+2.42 pp
RH4	+0.26 pp	+1.06 pp	+0.82 pp	+0.04 pp	+0.40 pp	+2.99 pp
RH5	+0.69 pp	+1.82 pp	+1.60 pp	+0.10 pp	+1.80 pp	+11.04 pp
RH6	+5.22 pp	+15.95 pp	+19.86 pp	+3.60 pp	+11.16 pp	+55.35 pp
RH7	+5.65 pp	+24.97 pp	+35.69 pp	+3.04 pp	+12.82 pp	+99.03 pp
RH8	+3.27 pp	+5.51 pp	+19.53 pp	+0.69 pp	+11.75 pp	+32.27 pp

Measure 4: Water recycling and reuse (ApR). This measure involves the treatment and reapplication of wastewater for various purposes, fostering a more sustainable approach to water management. Employing advanced water treatment technologies to remove contaminants and impurities from wastewater makes it suitable for reuse for non-potable purposes, such as irrigation (providing nutrients to crops) or industrial settings where water is treated and reused within the manufacturing processes. This measure reduces the demand for freshwater in activities that do not require drinking-quality water (United Nations Environment, 2017). Nevertheless, it is important to highlight that before water allocation for economic activities, it is necessary to guarantee ecological and environmental flows, both for surface waters and groundwater.

To calculate the benefits of water recycling and reuse, the WEI+ was recalculated considering the water availability from modelling simulations and considering the wastewater available for recycling is 80% of the municipal water supply, industry and tourism.

The comparison of projected changes in the WEI+ between scenarios with and without water recycling and reuse (WP4 Table 12 vs. Table 3.1.15) reveals an improvement of approximately 3 pp (up to 16 pp) with the implementation of enhanced water recycling practices. The most significant impact is observed for RH8, where it was estimated a change from moderate to severe scarcity conditions by the end of the century; high water stress is now projected, highlighting the crucial role these measures have in establishing alternative water sources to precipitation and meet water demands in the region.

Table 3.1.15 – Projected changes in WEI + (percent points) considering measure 4. Three future periods are shown: 2011-2040, 2041-2070, and 2071-2100, under all emission scenarios – RCP2.6, RCP4.5, and RCP8.5. The presented values refer to the multi-model ensemble mean.

River Basin	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
RH1	-0.18 pp	+0.05 pp	+0.20 pp	-0.25 pp	+0.06 pp	+1.09 pp
RH2	-0.89 pp	-0.42 pp	-0.16 pp	-1.03 pp	-0.35 pp	+1.49 pp
RH3	-0.91 pp	-0.12 pp	-0.07 pp	-1.00 pp	-0.40 pp	+1.00 pp
RH4	-1.14 pp	-0.64 pp	-0.52 pp	-1.25 pp	-0.82 pp	+0.75 pp
RH5	-3.95 pp	-2.40 pp	-2.38 pp	-4.23 pp	-2.61 pp	+0.31 pp
RH6	+1.04 pp	+4.66 pp	+13.08 pp	+0.04 pp	+6.73 pp	+46.11 pp
RH7	+0.69 pp	+4.22 pp	+18.07 pp	-0.78 pp	+5.49 pp	+82.54 pp
RH8	-3.06 pp	-0.51 pp	+5.14 pp	-3.58 pp	+0.24 pp	+17.96 pp

Other adaptation measures:

1) Soil moisture conservation techniques: Practices and strategies implemented to protect and enhance the physical, chemical, and biological attributes of the soil. Additionally, these methods also focus on increasing the soil's ability to retain moisture and enhancing aquifer strength, thereby providing support for agricultural activities. The following are some examples of such techniques for reducing excess soil moisture loss:

- Spreading manure or compost over the soil: This process integrates a valuable source of nutrients and organic matter into the soil (Un Environment 2017). Some important benefits in agriculture include the reduction of evapotranspiration, enhancement of soil fertility, improvement of soil structure, mitigation of soil erosion, and suppression of plant diseases.

- Mulching: Mulch is a protective layer of organic (or inorganic) material that is spread on the soil surface around the crops. Organic mulch options, such as straw, wood chips, and peat, contribute nutrients and humus to the plant root zone. In contrast, inorganic mulch, in the form of plastic or rubber, is commonly employed to inhibit weed growth.

The effectiveness of mulching is influenced by the climatic conditions and the quantity of precipitation in each area (Un Environment 2017). It influences the moisture content of soil by reducing the evaporation of water from the surface of the soil.

- Conservation tillage: Conservation tillage is a diverse set of agricultural practices that focus on managing the surface layer of the soil, reducing their loss relative to some form of conventional tillage. Conservation tillage can decrease surface runoff and increase infiltration by preserving residue cover on the soil surface.

These practices aim to minimise or eliminate the frequency or intensity of tillage operations and promote economic and environmental benefits. The most significant advantage of conservation farming systems is the significantly reduced soil erosion due to wind and water, along with an increased capacity for water infiltration in the soil (Un Environment 2017).

2) Rainwater harvesting for storage: Rainwater harvesting is a technology that involves the direct capture of rainfall runoff, either into open storage systems or from a range of surfaces like roofs, ground surfaces, roads, sidewalks, and specially designed artificial surfaces for this purpose (UN Environment 2017).

In general, these systems have a simple structure and components (such as tanks) and can include domestic systems, small surface reservoir systems for irrigation of small farmers, and large surface dam systems for large areas. Nevertheless, the need to ensure ecological and environmental flows for surface waters and groundwater should be taken into account.

3) Public water conservation campaigns: Public water conservation campaigns are an essential component of drought management efforts, contributing to the mobilisation of citizen attitudes and actively promoting improvements in water use efficiency. These campaigns involve awareness programs and should encompass educational institutions, communities, and organised community movements committed to water conservation, aiming for socioeconomic and environmental benefits.

Communication methods include traditional and social media, as well as direct communication like workshops, presentations, stakeholder dialogues, newsletters, interactive websites, and collaborative events (Un Environment 2017).

4) Awareness and training of farmers: It concerns actions and projects designed to provide specific training to farmers regarding the impacts of climate change on agriculture, providing them with the knowledge and skills necessary to adapt to these changes. This includes imparting knowledge into sustainable farming practices, introducing climate-resilient crop varieties, and fostering a deeper understanding of conservation agricultural techniques. The awareness and training of farmers has the potential to disseminate knowledge, enabling them to make decisions and implement practices that foster both productivity and environmental sustainability in response to climatic changes.

5) Progressive pricing: Pricing water and water-related services is an important economic instrument to enhance the efficiency of water use reflecting the scarcity of the natural resources in both public and private water sources, reinforcing social equity, and ensuring the financial sustainability of water services and operators. Progressive pricing means that the cost of water per unit of volume increases as the volume used increases. This approach encourages responsible water usage by imposing higher rates on larger consumption and could promote using alternative sources such as ApR, considering that the costs would compensate for their use.

6) Seawater desalination: A method that eliminates salt and other components to generate freshwater. The primary techniques employed for desalination are thermal treatment and membrane processes. In thermal treatment, heat is utilised to vaporise water, leaving behind the dissolved salts in a waste stream, which is then separated from the pure water. Meanwhile, membrane processes employ reverse osmosis and high pressure to drive saltwater through exceptionally fine, porous filters. These filters retain the salts, permitting pure water to emerge on one side of the membrane while directing the waste stream to the other side (Un Environment 2017).

7) Water retention landscapes: Water retention landscapes are structures designed to store water that also contributes to reducing erosion processes and enhancing water infiltration into the soil. The implementation of these water retention landscapes can be achieved through diverse terrain modelling techniques, including the creation of lakes, ponds, small reservoirs, ditches, bunds, and terraces, without compromising the e-flow regimes or river continuity.

This process involves mobilising conservation practices or interconnecting different solutions. These structures hold a crucial role in regions experiencing prolonged dry seasons and significant rainfall variability. They are also valuable in areas anticipating an increase in seasonal water availability due to climate change.

8) New reservoirs or connection between existing reservoirs: A reservoir is an expanded river or stream situated after the construction of a dam. These structures are designed and artificially implemented to store water for a variety of purposes, such as water supply, irrigation, hydroelectric power generation, flood control and recreation (Un Environment 2017). Reservoirs are essential components of water management systems, providing a reliable and controlled source of water for human activities.

Please note this measure requires a detailed hydrological analysis and an assessment of water demand before proceeding with new reservoirs. In the first place, procedures should be guaranteed to evaluate whether existing reservoirs are being used to their maximum capacity. Secondly, understand why several dams can no longer recover their storage (building more may not be worthwhile); and finally, assess the downstream consequences of their impacts, as the water quantity will decrease for existing uses downstream of new developments.

9) Water metering: This measure is mainly related to 'apparent' losses, which are defined as those associated with imprecise consumption measurements by the consumer or managing entities, data handling errors, or in circumstances of unauthorised consumption.

These losses can be managed through verification, calibration, and replacement of inefficient instruments, as well as through actions such as increasing efficiency in supply systems and monitoring and controlling consumption. Data management tools can also be employed to ensure that all meters are read consistently and accurately. Inspections of unauthorised uses are also important tools for managers seeking to minimise apparent losses.

Implementing this measure offers advantages such as minimising unnecessary abstraction at the source water, lowering the energy needed for water capture, treatment, and transportation, and fostering public awareness of water conservation. It also encourages water efficiency and sustainable behaviours.

10) Water entitlements: They constitute a legal mechanism where users are granted permission to utilise groundwater or surface water for a specified period, with the purpose and conditions stipulated in water permits, ensuring e-flow regimes.

The water permits apply to prospective water users who are required to request a licence or authorization for the implementation, expansion, and/or modification of any project involving surface or groundwater water use. It also extends to activities involving alterations to the flow, quantity, or quality of water through works or services.

The management of water resources through permits allows for quantitative and qualitative control of water use, enabling an equitable distribution of the resource and imposing use restrictions when necessary. Water permits also ensure the effective exercise of the rights and duties to access water resources by users. Exceptional conditions of water use during extreme events are also defined, with temporary suspension of rights.

3.1.5. Adaptation costs

To account for the adaptation costs of adaptation measures it is proposed:

1) **Selection of crops better suited to climate change projections**: These measures involve replacing corn with sunflower. It will be necessary to obtain information on the costs associated with sunflower cultivation (Including costs of labour, fertiliser application, seed costs, machinery costs, and irrigation costs) and the cost of corn cultivation per hectare. Calculating the difference between both costs and extrapolating it to the areas where corn cultivation is currently practised will allow for an estimation of the costs associated with crop substitution.

2) **Improving irrigation efficiency**: The average cost per hectare of implementing the drip irrigation system is necessary. This involves assessing the costs of materials, labour, and equipment required for installing the drip irrigation system. The total cost will be extrapolated based on quantifying the areas of crops that currently have a less effective irrigation scheme and could adopt dripping.

3) **Reducing system water loss and leakages**: For the cost calculation, there must be substantial interaction with decision-making institutions in the context of water resources and agriculture, namely APA and DGADR. This is because calculating the costs of reducing water losses and leakages in a system requires a detailed approach and consideration of various factors. Even when conducting an assessment focused only on the direct costs of implementing this adaptation measure, it will be necessary to identify the extent of the water system and its current infrastructure for each hydro-agricultural development. This

includes evaluating the quantity of water losses and existing leaks (information already available as Table 2), identifying the technology and solution for each Hydro-agricultural development to reduce water losses and leaks, estimating the costs associated with the implementation of technologies, including installation, training for operation, labour for implementation and maintenance of the solution.

Water recycling and reuse: To quantify the implementation costs of this measure (direct costs), strong communication with water decision-makers will be necessary, as adaptation solutions must be defined on a case-by-case basis, and the costs of infrastructure need to be estimated. This includes the improvement of some treatment facilities, and the creation of pipelines, and distribution systems. The scale and complexity of these infrastructure components will influence costs, so the solutions to be studied must be framed by the national water authority. The choice of water treatment technology plays a significant role in costs. Advanced treatment technologies, such as reverse osmosis or advanced oxidation processes, may be more expensive but can produce high-quality reclaimed water. Ongoing operational and maintenance costs must also be considered, along with the costs related to the energy required for treatment processes.

3.2. Forest Fires

Climate change imposes an overwhelming strain on individuals, companies, institutions, and governments, calling all those with responsibility to prepare viable and timely adaptation measures to secure the future prosperity of society (IPCC, 2023a). This challenge affects several sectors, from agriculture (Bento et al., 2021; Shahzad et al., 2021) and forests (Austin et al., 2020; Bento et al., 2023a) to health (Romanello et al., 2022; World Health Organization, 2021) and water resources (Marin et al., 2020; van der Laan et al., 2023). Among other natural hazards, weather-driven extreme events like vegetation fires, droughts, heatwaves, and extreme precipitation, including flash floods, are expected to take a toll on society as we know it (IPCC, 2023b).

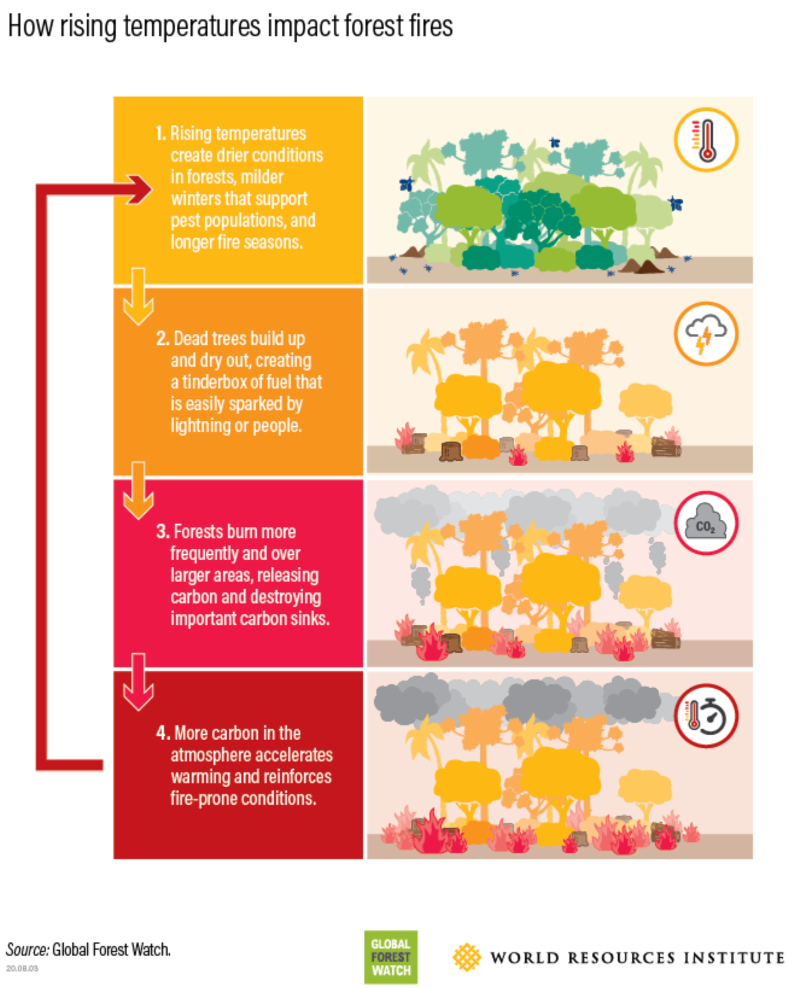


Figure 3.2.1 – Schematics showing how rising temperatures impact forest fires (source: Global Forest Watch).

Wildfire regimes and their intensity are projected to change considerably worldwide due to climate change (Krawchuk et al., 2009; Pausas and Keeley, 2021) (Figure 3.2.1). Recent studies provide plenty of evidence that support to a large extent this shift, namely in what concerns some of the most destructive and intense fires that have occurred in recent years in Australia, California, and the Amazon Forest (Boer et al., 2020; Keeley and Syphard, 2019; Libonati et al., 2022, 2021). Located in a climate change hotspot (Diffenbaugh and Giorgi, 2012; Giorgi, 2006; Sánchez-Benítez et al., 2018) at the western tip of the Mediterranean, the Iberian Peninsula, and Portugal in particular, is well-known for its summer fire occurrences, extensively studied by the scientific community (Amraoui et al., 2013; Bento et al., 2022; Calheiros et al., 2021; DaCamara et al., 2014; Garcia-Herrera et al., 2010; Nunes et al., 2019; Ramos et al., 2023; Russo et al., 2017; Santos et al., 2023; Trigo et al., 2006, 2016; Turco et al., 2019).

In recent years, continental Portugal has faced the most intense and destructive fires on record, namely those that took place during the 2017 season that burned more than 500,000 ha (Figure 3.2.2) and resulted in over 100 human fatalities (Ramos et al., 2023). The single fire event that took place in August 2018 in

Algarve (southern Portugal) was responsible for more than 25,000 ha of total burned area, destroyed dozens of homes and claimed thousands of animal lives (DGAPPF/DDFVAP, 2018). The recent 2022 fire season witnessed record-breaking fire danger indices across the country that steered a large fire event that devastated a considerable portion of the Serra da Estrela mountain range, a UNESCO Geopark and Portugal's largest natural park (Mendonça and Máguas, 2023). All these fire events caused substantial social and economic losses, with the 2017 fire season alone costing more than 1,000,000,000 € (Ramos et al., 2023), the event of 2018 in Algarve leaving over 100 people homeless (DGAPPF/DDFVAP, 2018), and the event of 2022 in Serra da Estrela affecting severely tourism and local producers (Mendonça and Máguas, 2023).

Recent records point towards a "new normal" where frequent extreme fire danger conditions and associated large fire events become part of everyday life during the warmer summer months (Bento et al., 2022). This prospect becomes even more worrisome when considering the non-stationary nature of climate evolution under climate change forcing and therefore the inevitability that this "new normal" is bound to be exceeded, according to climate change projections until the end of the 21st century. This report (see WP4) and Bento et al., (2023b) point out that summer fire danger in the Iberian Peninsula is expected to substantially increase in the future, with an expansion of the fire season from June to September. Northwestern Iberia, including northern Portugal and northwestern-to-central Spain, is projected to experience the largest increases in fire danger. These regions are particularly vulnerable due to their fire-prone vegetation (Trigo et al., 2006). However, projections differ among different scenarios, emphasising the need for distinct adaptation strategies to be promptly adopted by stakeholders and authorities.

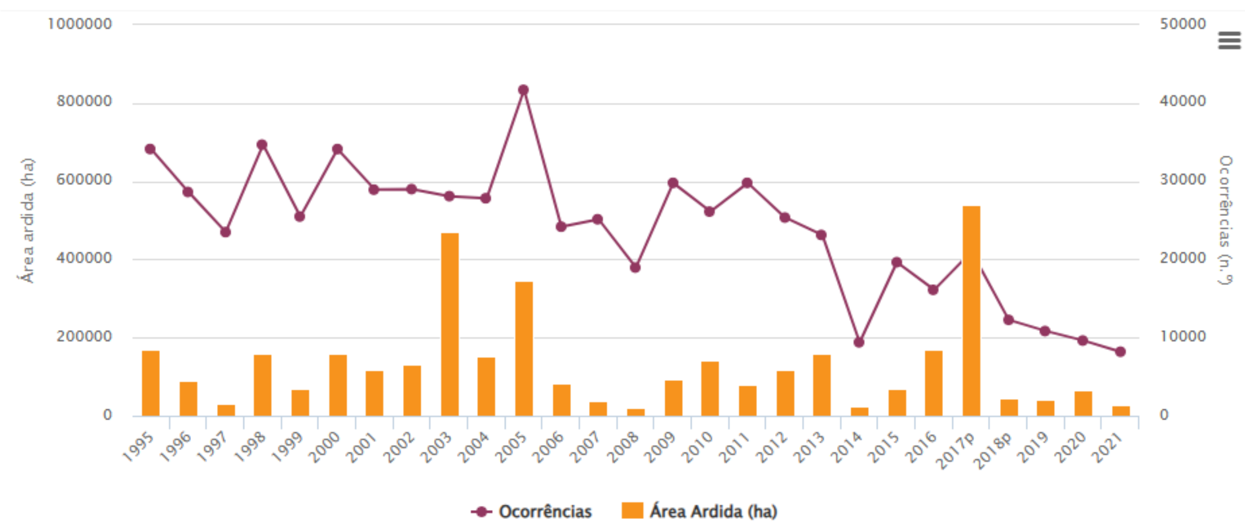


Figure 3.2.2 – Burned area and number of occurrences in Portugal by year (source: ICNF).

With the aim of assessing climate change impacts and implications, experiments focusing on dynamic or statistical downscaling of global climate models (GCMs) were designed within the framework of projects such as the Coordinated Regional Downscaling Experiment (CORDEX) (Giorgi et al., 2009; Jacob et al., 2020). Many authors have taken advantage of ensembles composed by several continental-scale simulations from CORDEX to assess climate change projections on various key variables to wildfire danger evaluation from a European scale to that of the Iberian Peninsula and Portugal. These studies systematically point to a decrease in mean precipitation along with an increase in extreme precipitation events (Soares et al., 2017), an increase in maximum and minimum temperature independently of the season of the year and emission scenario (Cardoso et al., 2019), and a decrease in 10-m wind speed over the northernmost part of Portugal in autumn and winter and an increase during summer months over the central country (Nogueira et al., 2019). Moreover, a number of works have recently focused on CORDEX multi-model experiences to analyse projections of wildfire danger indices in regions scattered over the globe (Faggian, 2018; Ruffault et al., 2018; Trnka et al., 2021; Varela et al., 2019).

The Canadian Forest Fire Weather Index System (CFFWIS) is one of the most well-known and widely used sets of meteorological fire danger indices. CFFWIS is composed of six components that rate fuel moisture and weather conditions' effects on fire behaviour (Van Wagner, 1974). The components rely on empirical relations between meteorological variables (temperature, precipitation, relative humidity, and wind speed) and characterise the level of stress of a standard fuel, namely that of a generalised Canadian jack pine forest (Stocks et al., 1989). These components include the fine fuel moisture code (FFMC), the Duff moisture code (DMC), the drought code (DC), the initial spread index (ISI), the build-up index (BUI), and the fire weather index (FWI). FWI provides valuable information on the role of meteorological conditions in favouring the build-up and spread of wildfires, and is particularly suitable for assessing meteorological fire danger over Mediterranean Europe; for instance, information about FWI is now an operational part of the emergency management services within the EU Copernicus program – the Fire Danger Forecast module of the European Forest Fire Information System (EFFIS) (San-Miguel-Ayanz et al., 2012). FWI has also been successfully used to improve the quality of fit of statistical models of the distribution of hotspots related to vegetation fires, either in terms of duration (DaCamara et al., 2014) or energy released (Pinto et al., 2018a); these models are on the basis of the Fire Risk Map product that is operationally disseminated by the Satellite Application Facility for Land Surface Analysis (LSA SAF) that is part of the ground segment of EUMETSAT (Trigo et al., 2011).

In a recent study, DaCamara et al., (2023) showed that the logarithm of Fire Radiative Power (FRP), i.e., the rate of energy released by vegetation fires, follows a distribution consisting of a doubly truncated lognormal central body with Generalised Pareto lower and upper tails. Nunes et al., (2023) then showed that the model is improved by incorporating FWI as a covariate in the parameters of the model, and that the improved model could be used to generate synthetic values of FRP associated to prescribed values of FWI.

In this report we aim at extending this approach to characterise fire activity in Portugal for different projected scenarios throughout the 21st century and to assess the impact of fire prevention policies based on FWI projections. For this purpose, we first consider satellite-retrieved values of FRP released by vegetation fires covering the 20-year period 2001-2020 and associated values of FWI as derived from reanalyzed meteorological fields. Then, following the procedure proposed by DaCamara et al., (2023) and Nunes et al., (2023), we fit the above-mentioned statistical model to the logarithm of FRP using FWI as covariate of the model parameters. We then rely on EURO-CORDEX RCMs to estimate future FWI in Portugal for the Representative Concentration Pathways (RCPs) RCP2.6, RCP4.5, and RCP8.5. Finally, we generate synthetic values of FRP for each of the RCPs. This procedure also allows assessing the impact of a given fire prevention policy based on FWI by randomly eliminating subsets of values of FWI according to the considered prevention policy, then generating synthetic values of FRP from the reduced set of FWI, and finally comparing against other distributions of generated sets of FRP associated to other policies and, in particular, comparing to a no prevention policy. This approach allows assessing the impact of different adaptation strategies that will assist decision-makers in implementing policies aiming at reducing the occurrence and impacts of large fire events. To the extent of our knowledge there is still no study available where fire policies are assessed based on estimates of FRP for future climate scenarios. Accordingly, we propose in this report to address the two following questions: (1) What is the future projected change in the probability of large fires in continental Portugal due to climate change, and how is this change affected by different greenhouse gas emission scenarios across the century? (2) What is the impact of different fire prevention policies? Should decision-makers implement all-summer policies, or should they restrict their attention to the most extreme fire danger days? Answers to these questions will be provided by leveraging an ensemble of regional climate models from the EURO-CORDEX initiative, MODIS observations of FRP, and the design of simple but illustrative strategies for fire reduction.

In the sense of adaptation to climate change, AGIF (Agência de Gestão Integrada de Fogos Rurais) also developed a report focused on the Portuguese adaptation to forest fires. The report states that to implement the National Plan for Adaptation (PNA) through the National Plan for Forest Restoration (PNGIFR), the use of risk analysis and management tools is essential. For this purpose, and based on the degree of implementation of the program and the results achieved by the processes of the National Forest Restoration System (SGIFR) until 2030, three scenarios were developed: the scenario *"Conseguimos"*, *"Quase lá"*, and *"Céu Negro"*. The next paragraphs summarise the three scenarios.

In the *"Conseguimos"* scenario, institutions and both public and private resources were successfully mobilised to activate the virtuous circle of forest economy. This ensured that landowners managed their assets collectively, efficiently channelling savings and funds from the National Recovery and Resilience Plan (PRR), Portugal 2030 (PT2030), and the Common Agricultural Policy (PAC) for the active management of forests and agro-forests, particularly in the northern and central coastal regions. This led to improved remuneration for both woody and non-woody assets and included revenue for environmental services provided. With strong commitment from forest, meat, cheese, and tourism industries, the areas affected by wildfires in 2017 were recovered. Management models implementing good forestry, pastoral, and fire prevention practices were realised. Activities associated with forest and silvopastoral management became cornerstones of territorial development, contributing to increased employment in rural areas. The dependence on external energy sources in these territories decreased due to local biomass collection and shortened associated logistical chains. Especially north of the Tagus River, the quantity of vegetation around homes significantly decreased. Fuel management strips and mosaics were implemented, contributing to the effectiveness of firefighting operations. Through alternatives like composting and increased awareness, the population changed its behaviour in using fire for waste management. The number of wildfires reduced by 80%, and on days of higher risk, the average number of fires was less than 40. Despite increased fire risk due to extreme weather conditions, institutional reinforcement of public and private actors allowed for operations that reduced danger (vegetation and ignitions) in all priority areas. This resulted in increased efficiency of the suppression system, which also transformed with specialised and empowered agents. All agencies were able to cooperate, ensuring the integrated and efficient functioning of the operational system. Operational forces carried out missions according to international training and operation standards, adapting tactics and techniques based on meteorology, topography, and vegetation type. This ensured that all fires were perimeter-controlled, and as a consequence, the number of re-ignitions was less than 3%. In rare larger events, populations were timely confined or evacuated, and damages were promptly covered by parametric insurance. Burned areas exceeding 500 hectares represented less than 0.3% of fires and immediately underwent emergency stabilisation and recovery operations, with plans and programs executed promptly. In this scenario, from 2020 to 2030, casualties from rural fires and the total burned area were minimised. The total burned area, compared to the *"Céu negro"* scenario of inaction, decreased by 71%, reaching international metrics, totalling 660,000 hectares (60,000 hectares/year or 0.9% incidence).

In the *"Quase lá"* scenario, only a portion of the financial resources from Portugal 2030 (PT2030) and the Common Agricultural Policy (PAC) could be mobilised, with priority given to their application in areas managed by the State, communal lands, parks, and nature reserves, implementing forestry and fuel management programs. North of the Tagus River, the capacity building of owner organisations did not materialise, and the improvement in remuneration for goods and services provided by forest spaces was insufficient to mobilise landowners. Forest management aggregated by landowners remained localised, and market failures persisted, now extending to ecosystem services. Exporting companies did not fully embrace their social and environmental responsibility, perpetuating dynamics of unsustainable management of production forests. Regulatory failures did not solidify local initiatives for biomass-based energy production, and the few fostered initiatives were absorbed by market asymmetries. The areas affected by wildfires in 2017 were not recovered with planning and aggregated management, with a significant portion of these areas still unmanaged, leading to an increase in fuel load. However, fuel management strips and mosaics were implemented only in public areas and communal lands, and around homes, effective prevention efforts were observed, contributing to the effectiveness of protection operations for most villages and critical forest areas. The population used fire less frequently for waste management, resulting in a reduction of over 50% in the number of fires, but not significantly in the central and northern sub-regions. On the worst days, these regions continued to contribute to an average of 100 fires. Operational forces did not use fully compatible systems and processes, although they attended comparable but non-integrated qualification programs. In the face of extreme events, adverse weather conditions, and territories with fuels that enhance rapid and intense fire behaviour, the suppression system was overwhelmed and only ensured the perimeter defence of villages and communities, managing to mostly confine or evacuate the population. Weaknesses in the command and control of complex events did not ensure that all fires had perimeter control, and the number of reignitions was reduced to less than 10%. Areas burned over 500 hectares were not fully recovered, and less productive areas saw the abandonment of forestry activities. Economically, forestry and silvopastoral activities continued to lose significance, exacerbating the imbalance in the agroforestry trade balance. In this scenario, climate agenda objectives were not met, although the territory showed resilience in areas managed by the State, communal lands, and nature parks. The total burned area by 2030 reduced by 33% compared to the "inertia" scenario, totalling 1,501,500 hectares (136,500 hectares/year on average or 2.1% incidence).

In the *"Céu negro"* scenario of inaction, fundamental improvements were not realized, and efforts to access financial resources from the PPT, Portugal 2030 (PT2030), and the Common Agricultural Policy (PAC) had no impact on the territory. Cumulatively, private entities disinvested in forestry and silvopastoral activities. Public and private institutions were not capacitated, and numerous legislative initiatives remained unrealized. Owner aggregation was limited to specific territories, market failures intensified, and the anarchic and extractivist exploitation by most forest operators deepened, resulting in the exclusion of Portuguese brands from markets with stringent criteria for social and environmental responsibility. Without fair valuation of their products and environmental services, forest management abandonment dynamics extended to the central and northern coastal areas, contributing to an increased risk of urban fires, which, meanwhile, also continued to expand unchecked. With no alternatives for waste disposal, the population continued to use fire frequently, given insufficient enforcement. Despite an increased number of high-risk fire days, the number of negligent fires persisted, and on the worst days, around 300 fires ignited, with 15% resulting from reignitions of events from previous days. Over half of the areas burned in 2017 were engulfed again, even more rapidly and intensely, in multiple events. This time, there was some anticipation and mobilisation of resources, avoiding the magnitude of the tragedy then, but still with human casualties. However, the reinforcement of equipment and operations couldn't prevent the loss of lives and significant material damage. Weaknesses in command and control of complex events worsened due to interagency cooperation absence and non-compliance with defined procedures, with forces operating in events in a non-integrated manner. In this scenario of territorial and institutional collapse, costs and damages escalated, and climate agenda objectives were not met, despite some resilience in areas managed by the State and natural parks. The total burned area between 2020 and 2030 reached 2,255,000 hectares (205,000 hectares/year or a 3.2% incidence rate).

Considering these scenarios developed by AGIF and associated risks, the critical success factors pivotal for prevention, risk mitigation, and realising the "Achieved" scenario are multi-faceted. Firstly, a focus on integrated planning is crucial, spanning national, regional, sub-regional, and municipal levels. This entails maintaining a consistent approach aligned with regional priorities. Simultaneously, efforts for capacity-building extend to both public and private institutions, aligning with the specifications of the new system (SGIFR) and its organic structure. To strategically address action areas, incentives are directed comprehensively, embracing preparation, prevention, pre-suppression, suppression, and post-event measures. Priority is assigned to areas with the highest potential damage in major fire incidents. Recognizing the importance of sustained investment, continual support is required for the enhancement and maintenance of rural spaces. Qualification of SGIFR Agents involves specialised training and professionalisation. Behavioural change is integral, stemming from all preventive actions, spanning fuel management, education, and effective communication. Ensuring efficient management of prevention and firefighting resources takes precedence, ensuring readiness and commitment. Funding is reallocated based on identified system priorities. Ongoing monitoring and improvement of procedures are essential, aligning with new guidelines emerging from the process chain. At the practical level, pilot units at the NUTSIII level are proposed for implementing the National Plan for Forest Fires (PNA) and the associated process chain. Consequently, the assurance of conditions within three major domains is imperative throughout the National Plan for Forest Fires (PNGIFR) period:

1) Effective execution of the PNGIFR for realizing goals and objectives.

2) Governance plays a pivotal role in achieving a paradigm shift in both operational and organisational aspects, converging towards integrated management of rural fires.

3) System efficiency, including continuous improvement processes, is vital to enhance and sustain its capacity.

3.2.1. Inaction costs

To assess the costs associated with inaction, it is essential to analyse a time series of monetary losses and damages resulting from forest fires, measured in euros (€). This analysis should encompass annual costs over an extended timeframe, such as the period from 1991 to 2020.

3.2.2. Adaptation measures

In recent years, the Earth's climate has undergone significant transformations, giving rise to a host of challenges that impact ecosystems worldwide. One of the most pressing issues is the escalating frequency and intensity of forest fires, exacerbated by the far-reaching effects of climate change. As temperatures rise, precipitation patterns shift, and vegetation dries out, forests become increasingly susceptible to ignition and rapid spread of wildfires. The consequences of these fires extend beyond immediate ecological damage, affecting air quality, human health, and biodiversity. In light of this escalating threat, the imperative for societies and ecosystems alike is to adapt to the changing dynamics of forest fires induced by climate change. Understanding, preparing for, and mitigating the impacts of these fires are not only crucial for safeguarding our natural landscapes but also for ensuring the resilience and sustainability of communities that depend on these ecosystems. This adaptation involves a multi-faceted approach, encompassing proactive forest management, community engagement, and the development of innovative technologies. As we delve into the intricacies of this challenge, it becomes apparent that effective adaptation is not merely a choice but a necessity in navigating the evolving landscape of climate-induced forest fires.

Forest fire adaptation lines of action can be substantiated on different strategies to be applied by forest managers. Among those, we summarise below the ones that are more frequently applied and that were proposed by the consortium for discussion (see WP1) and show a map of Portugal with some measures pointed out (Figure 3.2.3).

1. Controlled biomass burning:

Controlled biomass burning refers to the intentional, planned ignition of vegetation under managed conditions, often for specific purposes such as ecosystem restoration, agricultural management, or reducing the risk of uncontrolled wildfires. This practice involves carefully regulating the timing, intensity, and extent of the burn to achieve desired outcomes while minimising negative impacts. Controlled biomass burning serves as a valuable adaptation measure for several reasons. First, it can reduce the accumulation of flammable vegetation, acting as a preventive measure against the occurrence of more severe and uncontrollable wildfires. By strategically burning smaller areas under controlled circumstances, the risk of large-scale, destructive fires can be mitigated. Second, controlled burns contribute to ecosystem health by promoting biodiversity, nutrient cycling, and the regeneration of certain plant species that are adapted to fire. This intentional management of fire helps maintain ecological balance and resilience in fire-prone ecosystems. Lastly, controlled biomass burning can have positive effects on air quality. By conducting burns under controlled conditions, it is possible to minimise the release of harmful pollutants compared to uncontrolled wildfires. This aspect is crucial for protecting human health and maintaining environmental quality. In essence, controlled biomass burning is a proactive and strategic approach to harnessing the beneficial aspects of fire while minimising its potential negative impacts. As a tool in the broader toolkit of adaptive strategies, it plays a role in fostering sustainable coexistence between human communities and fire-prone ecosystems in the face of climate change.

2. Reduction of fuel continuity:

The reduction of fuel continuity is an adaptation measure that involves modifying the arrangement and density of vegetation to create discontinuities or breaks in the fuel bed, thereby inhibiting the continuous spread of wildfires. This approach aims to decrease the availability of flammable material, limiting the potential for wildfires to rapidly advance and intensify. One of the primary strategies in fuel continuity reduction involves thinning and spacing vegetation, particularly in areas where the fuel load is dense and continuous. By creating gaps between plants and reducing the overall biomass, the likelihood of fire spreading from one plant to another is diminished. This process is often implemented through mechanical thinning, prescribed burns, or a combination of both. This adaptation measure is effective for several reasons. First, it acts as a barrier to the horizontal movement of wildfires, providing a level of containment and reducing the overall size and impact of the fire. Second, by breaking up the fuel continuity, the intensity of the fire is often reduced, making it more manageable for firefighting efforts. Finally, this approach contributes to overall ecosystem health by promoting a more natural and sustainable balance in vegetation density. In the context of climate change-induced wildfires, the reduction of fuel continuity stands as a practical and ecologically sound adaptation strategy. It aligns with the broader goal of enhancing the resilience of ecosystems and communities to the evolving challenges posed by changing climate conditions.

3. Enhancing vegetation resilience to fire:

Enhancing vegetation resilience to fire is an adaptive strategy focused on fortifying plant communities against the impacts of wildfires in the context of a changing climate. This approach recognizes the inevitability of fires in fire-prone ecosystems and aims to promote the ability of vegetation to withstand and recover from these disturbances. Several key components contribute to the effectiveness of this adaptation measure:

- Species Selection and Diversity: Choosing and promoting plant species that are naturally adapted to fire can enhance resilience. Some species have evolved mechanisms such as fire-resistant bark, seeds that survive fire, or the ability to resprout after a fire event. Additionally, maintaining a diverse array of plant species fosters ecological resilience, as different species may respond to fire in varied ways.
- Habitat Restoration: Rehabilitating degraded ecosystems through replanting and restoration efforts can improve overall vegetation health and resilience to fire. This involves re-establishing native plant communities, which often have evolved with fire as a natural part of their ecological processes.
- Fuel Management: While reducing fuel continuity focuses on altering the arrangement of vegetation, enhancing vegetation resilience involves managing the types and quantities of fuels. This may include selective thinning, removing dead or overly dense vegetation, and promoting a more fire-resilient vegetation structure.
- Climate-Responsive Practices: Considering the changing climate conditions, adaptive measures may involve adjusting land management practices to accommodate shifts in temperature, precipitation patterns, and other climatic factors. This ensures that vegetation management strategies align with the evolving environmental context.
- Community Engagement: In some cases, enhancing vegetation resilience involves collaborative efforts with local communities. This may include raising awareness about fire-adapted landscaping, encouraging fire-wise practices around homes, and fostering a broader understanding of the role of vegetation in mitigating fire impacts.

By bolstering the resilience of vegetation to fire, this adaptation strategy contributes to the long-term sustainability of ecosystems and helps communities better cope with the increasing challenges posed by climate change-induced wildfires. It emphasises a proactive and holistic approach to managing landscapes in the face of evolving environmental conditions.

4. Reducing the population's vulnerability to fire:

Reducing the population's vulnerability to fire is a critical adaptation strategy aimed at minimising the potential impact of wildfires on human communities. This multifaceted approach recognizes that, in addition to managing the ecological aspects of fire, it is essential to enhance the resilience and preparedness of human populations. Here are key components of this adaptation measure:

- Community Planning and Zoning: Developing and enforcing land-use plans and zoning regulations that consider the risk of wildfires is essential. This involves avoiding construction in high-risk areas and implementing measures to create defensible spaces around homes and infrastructure.

- Early Warning Systems: Establishing effective early warning systems can provide communities with timely information about potential wildfire threats. This includes alert systems, communication protocols, and evacuation plans to ensure that residents are informed and can take appropriate action well in advance.
- Education and Outreach: Raising awareness about the risks of wildfires and promoting fire safety education is crucial for reducing vulnerability. This involves educating the public about preventive measures, evacuation procedures, and the importance of creating defensible spaces around properties.
- Infrastructure Design: Implementing fire-resistant building materials and landscaping practices can contribute significantly to reducing the vulnerability of structures to wildfires. Creating defensible zones around homes, which involve modifying the vegetation to decrease fire intensity, is a key aspect of this strategy.
- Emergency Preparedness and Response: Enhancing community preparedness and response capabilities is vital. This includes training residents in fire-safe practices, conducting drills, and ensuring that emergency services are well-equipped and coordinated to handle wildfire incidents effectively.
- Social and Economic Support: Recognizing and addressing the social and economic vulnerabilities of communities is crucial. This involves providing support for vulnerable populations, such as the elderly or economically disadvantaged, to ensure that they have the resources and assistance needed to cope with and recover from wildfires.
- Collaboration and Partnerships: Building partnerships between local communities, government agencies, non-profit organisations, and other stakeholders is essential for effective wildfire risk reduction. Collaborative efforts can lead to more comprehensive and integrated approaches to community resilience.

By reducing the population's vulnerability to fire, this adaptation strategy seeks to create more resilient and prepared communities capable of withstanding and recovering from the impacts of wildfires. It emphasises the importance of a holistic and community-centred approach to wildfire risk reduction in the face of a changing climate.

5. Reducing ignitions through awareness campaigns:

Reducing ignitions through awareness campaigns is a targeted adaptation strategy focused on minimising the human-induced causes of wildfires by raising public awareness and promoting responsible behaviour. This proactive approach recognizes that a significant portion of wildfires is attributed to human activities, such as discarded cigarettes, campfires, equipment use, and power lines. Here are key elements of this adaptation measure:

- Education and Outreach: Awareness campaigns aim to inform the public about the potential consequences of human activities that can lead to wildfires. This includes educating individuals about fire-safe practices, proper disposal of cigarette butts, and the responsible use of equipment in fire-prone areas.
- Communication Strategies: Effective communication is crucial in conveying the risks associated with human-caused ignitions. Utilising various communication channels, such as social media, community meetings, and educational materials, helps disseminate information to diverse audiences and encourages a collective understanding of the importance of fire prevention.
- Regulatory Compliance: Awareness campaigns often emphasise adherence to existing regulations and restrictions related to fire prevention. By promoting compliance with fire bans, restrictions, and safety guidelines, these campaigns aim to reduce the likelihood of accidental ignitions during periods of heightened fire risk.
- Fire Safety Guidelines: Providing clear and concise fire safety guidelines is essential. This may include information on safe campfire practices, proper disposal of flammable materials, and the importance of reporting potential fire hazards promptly.
- Targeted Messaging: Tailoring messages to specific demographics and geographic areas can enhance the effectiveness of awareness campaigns. Understanding the unique challenges and behaviours of different communities allows for more precise communication and engagement.
- Partnerships with Stakeholders: Collaboration with stakeholders such as local communities, businesses, outdoor recreation organisations, and government agencies strengthens the impact of awareness campaigns. Joint efforts can amplify the reach of messages and foster a sense of shared responsibility for fire prevention.
- Behavioural Change Initiatives: Beyond imparting knowledge, awareness campaigns often aim to influence behavioural change. This may involve promoting a cultural shift towards responsible fire behaviour and fostering a sense of individual and collective responsibility in preventing human-caused ignitions.

By addressing the root causes of many wildfires—human activities—awareness campaigns play a crucial role in reducing ignitions. This adaptation strategy empowers communities to actively participate in fire prevention efforts, ultimately contributing to the protection of landscapes, ecosystems, and the safety of individuals in the face of a changing climate.

6. Increasing response capacity in wildfire situations:

Increasing response capacity in wildfire situations is a vital adaptation strategy designed to enhance the effectiveness and efficiency of emergency response efforts when wildfires occur. This approach recognizes that rapid and well-coordinated responses are essential for minimising the impact of wildfires on both human communities and natural landscapes. Here are key components of this adaptation measure:

- Training and Skill Development: Providing comprehensive training for firefighters, emergency responders, and community members ensures that they possess the necessary skills to effectively combat wildfires. This includes training in fire behaviour, incident command systems, evacuation procedures, and the use of firefighting equipment.
- Equipment and Technology: Ensuring that firefighting agencies have access to modern and well-maintained equipment is crucial for an effective response. This includes firefighting vehicles, aircraft, communication systems, and specialised tools designed for wildfire suppression.
- Coordination and Collaboration: Establishing robust coordination mechanisms among local, regional, and national agencies is essential. This involves pre-established communication protocols, joint training exercises, and collaborative planning to ensure a seamless and coordinated response to wildfires.
- Early Detection Systems: Implementing early detection systems, such as surveillance technology and monitoring networks, enhances the ability to identify and respond to wildfires in their early stages. Rapid detection allows for quicker response times and more effective containment of fires.
- Community Involvement: Engaging local communities in wildfire response efforts is crucial. Community-based organisations, volunteer groups, and trained residents can play a vital role in supporting official firefighting efforts, evacuation procedures, and post-fire recovery initiatives.
- Resource Mobilisation: Adequate resource allocation, including financial resources, personnel, and equipment, is essential for building response capacity. This ensures that firefighting agencies have the necessary resources to deploy quickly and effectively in the event of a wildfire.
- Preparedness Planning: Developing and regularly updating emergency response plans at the local, regional, and national levels is a fundamental aspect of increasing response capacity. These plans should address various scenarios, incorporate lessons learned from past incidents, and involve all relevant stakeholders.
- Research and Innovation: Investing in research and innovation to improve firefighting techniques, technology, and strategies enhances response capacity. This includes developing and implementing new firefighting technologies, fire-resistant materials, and strategies for managing complex wildfire scenarios.

By bolstering the response capacity in wildfire situations, this adaptation strategy aims to minimise the negative impacts of wildfires on human lives, property, and ecosystems. It underscores the importance of proactive planning, continuous training, and collaboration to effectively address the increasing challenges posed by wildfires in the context of a changing climate.

7. New measures proposed by the stakeholders during the trans-sectoral workshop (WP1):

In the framework of the National Roadmap for Adaptation to Climate Change XXI, a workshop with end-users and stakeholders occurred and some new measures were suggested:

- **Ensuring income through the compensation for ecosystem services**: involves providing financial incentives to landowners or communities for the conservation and sustainable management of natural resources and ecosystems. This approach recognizes and rewards the valuable services that ecosystems provide, such as carbon sequestration, water purification, and biodiversity conservation. It is considered a good adaptation measure for several reasons. Firstly, it provides a financial incentive for individuals or communities to engage in sustainable land management practices, promoting the conservation of ecosystems. Secondly, by attaching economic value to ecosystem services, it encourages a shift towards more environmentally friendly practices, fostering long-term sustainability. Thirdly, it contributes to the equitable distribution of benefits, ensuring that those responsible for preserving ecosystems receive compensation for their conservation efforts. Ultimately, ensuring income through compensation for ecosystem services aligns economic interests with environmental conservation, creating a win-win scenario for both communities and the ecosystems they depend on.
- **Settling the population in rural areas**: involves encouraging or incentivizing people to live in less densely populated, often rural or semi-rural regions. This adaptation measure is employed to alleviate urban congestion, promote sustainable land use, and enhance resilience to environmental challenges. By redistributing population centres, it aims to reduce the strain on urban infrastructure, protect natural ecosystems, and contribute to the overall well-being of communities. Settling populations in rural areas is considered a good adaptation measure for several reasons. Firstly, it can ease the burden on urban infrastructure, such as transportation, housing, and sanitation, reducing the environmental impact associated with urban development. Secondly, dispersing populations into rural areas may contribute to a more equitable distribution of resources and economic opportunities. Thirdly, rural settlement can enhance resilience by diversifying livelihoods, fostering self-sufficiency, and reducing the vulnerability of concentrated populations to environmental and societal shocks. While this measure offers potential benefits, successful implementation requires careful consideration of factors such as infrastructure development, access to essential services, and the preservation of rural landscapes. Moreover, it necessitates addressing challenges related to cultural preferences, employment opportunities, and ensuring that rural settlements have the necessary amenities to support a high quality of life.
- **Enhancing the landscape and the services provided by the forest**: involves implementing strategies to optimise the ecological, economic, and social benefits derived from forest ecosystems. This adaptation measure recognizes the multifaceted role of forests in providing essential services such as carbon

sequestration, biodiversity conservation, water regulation, and recreational opportunities. This approach is considered a valuable adaptation measure for several reasons. Firstly, it focuses on sustainable forest management practices that maintain ecosystem health and resilience. This includes techniques like afforestation, reforestation, and selective logging that support biodiversity and contribute to carbon storage. Secondly, enhancing forest landscapes can improve water quality and regulate water flow, mitigating the impact of extreme weather events such as floods and droughts. Thirdly, well-managed forests provide economic benefits through timber production, non-timber forest products, and ecotourism, thereby supporting local livelihoods. By integrating ecological, economic, and social considerations, this adaptation measure promotes a holistic approach to forest management. It aligns with the broader goal of creating resilient ecosystems that can withstand the impacts of climate change while meeting the diverse needs of communities that depend on forest resources. Additionally, by enhancing the overall services provided by forests, this measure contributes to the long-term sustainability of these vital ecosystems.

- **Creation of flow chains and valorization for pruning biomass and fuel management**: involves establishing organised processes and economic incentives to manage and utilise biomass, particularly from pruning activities in forests. This adaptation measure acknowledges the significance of addressing fuel loads and promoting sustainable practices in forest management. This approach is considered beneficial for several reasons. Firstly, it addresses the issue of accumulated biomass resulting from pruning activities by establishing systematic flow chains. This involves the organised collection, transportation, and processing of pruned biomass, reducing the risk of wildfires associated with excessive fuel loads. Secondly, the valorization aspect focuses on adding value to the biomass, often through conversion into bioenergy, biochar, or other valuable products. This not only helps in waste reduction but also contributes to the development of a bio-based economy. By creating flow chains and valorization processes, this adaptation measure aligns with broader sustainability goals. It helps mitigate the risk of uncontrolled wildfires, supports responsible forest management, and promotes the transition to renewable and environmentally friendly energy sources. Additionally, it fosters economic opportunities by tapping into the potential of biomass as a valuable resource, contributing to both ecological resilience and socio-economic development.

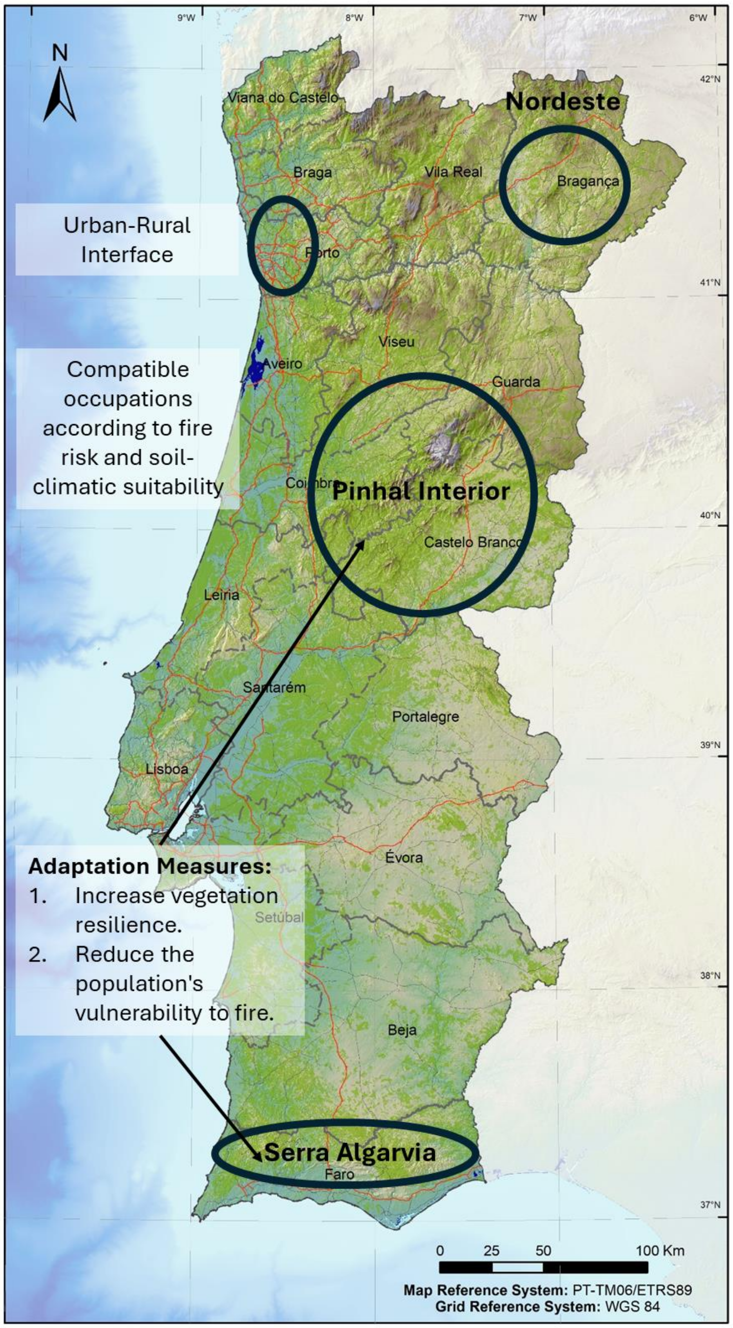


Figure 3.2.3 – Spatialization of adaptation measures discussed in the sector of Forest Fires.

Countries worldwide are actively implementing a range of strategies to adapt to the escalating threat of forest fires intensified by the impacts of climate change. In Australia, a country frequently grappling with severe wildfires, comprehensive measures have been set in motion. These include not only the enhancement of early warning systems and community education campaigns but also substantial investments in firefighting capabilities. Additionally, a significant focus has been placed on implementing prescribed burns, a strategic practice aimed at reducing fuel loads and enhancing the overall resilience of ecosystems to withstand fire events. In the United States, where wildfires have become increasingly prevalent, particularly in states like California, adaptive strategies encompass a diverse set of initiatives. These range from the implementation of prescribed burns to updating building codes to ensure the construction of fire-resistant structures. Recognizing the importance of addressing the wildland-urban interface, efforts have been directed towards promoting community-level resilience through targeted measures and educational campaigns. Canada, known for its vast landscapes and diverse ecosystems, is investing substantially in research endeavours to comprehend the intricate dynamics of climate change impacts on wildfires. This has led to the implementation of enhanced monitoring systems and early warning mechanisms. Simultaneously, efforts are being made to actively engage communities, fostering improved preparedness and understanding of the local factors influencing fire risks. In Spain, a country that has witnessed its share of devastating wildfires, adaptive measures include a combination of technological advancements and community-oriented strategies. Improved firefighting technology and early detection systems are being complemented by community training initiatives. Moreover, forest management practices have been implemented to strategically reduce fuel loads, contributing to heightened ecosystem resilience. Sweden, with its commitment to early detection and rapid response, has directed efforts towards bolstering surveillance capabilities. Investments in air surveillance technology, firefighting equipment, and collaborative agreements with other European nations contribute to a comprehensive strategy. The aim is to not only detect wildfires early but also to respond swiftly and effectively, minimising the potential impact on ecosystems and communities. These global examples underscore the diverse and nuanced nature of the challenge posed by climate change-induced forest fires. Adaptation strategies are dynamic and multifaceted, encompassing technological advancements, ecological considerations, and community-centric approaches. As countries collaborate and share best practices, there is a growing recognition of the importance of integrating indigenous knowledge into these adaptive strategies, acknowledging the wealth of insights that local communities can contribute to the ongoing global effort to mitigate the impact of wildfires.

Implementing adaptation strategies to forest fires under the context of climate change is riddled with various limitations and difficulties, reflecting the complexity of the challenge at hand. A primary obstacle lies in resource constraints, where many countries, especially those with limited financial capacities, struggle to invest adequately in advanced firefighting equipment, monitoring systems, and community outreach programs. The increasing scale and magnitude of wildfires under climate change pose a significant challenge, necessitating a reevaluation of current firefighting methods. The expanding wildland-urban interface adds complexity, requiring tailored adaptation strategies to balance ecosystem health and human safety. However, human activities, such as land-use practices and the use of fire-prone areas for agriculture or development, contribute significantly to wildfire risks, making changing human behaviour a formidable task. Climate uncertainty introduces challenges into adaptation planning, as accurate long-term projections for temperature, precipitation, and fire risk may be difficult to predict. This uncertainty complicates the development of adaptive strategies resilient to future climate scenarios. Additionally, some adaptation strategies, such as prescribed burns, may have unintended ecological consequences, requiring careful consideration and adaptive management approaches. Governance challenges, including coordination between different levels of government, agencies, and stakeholders, hinder the development and implementation of effective policies to address wildfire risks. Conflicting interests may impede progress, and policy implementation lag can further delay the translation of policies into on-the-ground actions. Engaging communities in proactive measures poses challenges, as individuals and communities may be resistant to changes in land management practices or lack awareness of the risks. Overcoming cultural barriers and ensuring inclusive decision-making processes are critical aspects of successful adaptation. Technological limitations, such as remote sensing and monitoring technologies not covering all regions, may hinder timely and accurate wildfire information. Access to cutting-edge technology may also be restricted in certain areas. Forest fires' interconnected nature with broader environmental and social challenges, including deforestation, biodiversity loss, and socio-economic disparities, necessitates a holistic approach that goes beyond fire-specific strategies. Navigating these limitations and difficulties requires a collaborative, interdisciplinary, and adaptive approach. Overcoming these challenges will necessitate ongoing research, innovation, and a commitment to developing and revising strategies as the understanding of climate change impacts on wildfires evolves. Additionally, international collaboration is crucial for sharing knowledge, resources, and best practices in the global effort to adapt to the changing dynamics of forest fires.

In this context, our primary emphasis is on adaptation measures that can be effectively modelled using meteorological variables alone. It is important to highlight that meteorological factors account for a significant portion of the variation in fire characteristics, making them an effective resource for adaptation strategies. Consequently, our focus here revolves around strategies aimed at diminishing the likelihood of ignition events associated with a specific energy release, namely, a given Fire Radiative Power (FRP). For further information on these models, please refer to WP4.3.

Fire prevention policies are compared by reducing the size of the synthetic samples of log10(FRP) by randomly eliminating a predefined fraction of values when they are associated to values of FWI within a given range. The fraction of values to be randomly eliminated and the ranges of FWI are defined according to the chosen fire prevention policy. The following three strategies are tested as conceptual models of fire prevention:

1) **<u>Strategy 1</u>**: This strategy involves randomly reducing 50% of values of log10(FRP) that are associated to values of FWI that are larger than the median of the sample. Implementing Strategy 1 implies involving large human and material resources since it implies taking preventive actions over regions of moderate to high fire risk.
2) **<u>Strategy 2</u>**: Under this strategy, the reduction fraction varies according to the range of FWI of the sample. When FWI falls between the 75th and 90th percentiles of the sample, 50% of the log10(FRP) instances are randomly reduced. When FWI falls between the 90th and 95th percentiles of the sample, stricter measures are adopted that allow for a 90% reduction of log10(FRP) instances. Finally, when FWI exceeds the 95th percentile of the sample, even stricter measures are adopted leading to a 95% reduction in log10(FRP) instances. This strategy calls for a more balanced approach, combining proactive measures with more strict fire suppression efforts over regions of high fire danger.
3) **<u>Strategy 3</u>**: This methodology only involves randomly reducing 95% of the log10(FRP) instances when FWI surpasses the 95th percentile of the sample. This approach requires strong preparedness to act at very high levels of fire danger, focusing on swift and decisive firefighting measures over regions of extreme fire danger. Strategy 3 is designed to address the most critical fire scenarios and aims at mitigating the impacts of very severe wildfires, while drastically diminishing the number of times when such a drastic approach is implemented.

The impact of each Strategy is then quantified by the respective percentage reduction defined as:

$$impact(\%) = \frac{exc(FRP_{original}) - exc(FRP_{filtered})}{exc(FRP_{original})} \times 100 \qquad (1)$$

where exc(FRP) is the probability of exceeding a given log10(FRP) value for the original and the filtered data sets according to the Strategy considered. This exercise is repeated for ERA5, the 13-member EURO-CORDEX historical RCM ensemble, as well as the future ones, for the three scenarios and time windows. The percentile of FWI is computed for ERA5 and for the historical period. For the future scenarios, the value used of the percentile is the one obtained from the historical climate change assessment.

In the case of the historical simulations, Strategy 1 (Figure 3.2.4 top panels) leads to a reduction in the probability of exceedance of log10(FRP) by about 10% for fires with 100 MW, about 25% for fires with 1000 MW, and up to about 40% for very intense fires. In the case of Strategy 2 (Figure 3.2.4 middle panels), the projected decrease is about 15% for 100 MW, 40% for 1000 MW, and about 65% for very large log10(FRP). Finally, for Strategy 3 (Figure 3.2.4 bottom panels), the impact is close to 0% for 100 MW, 20% for 1000 MW, and 45% for very large log10(FRP).

Regarding the future projections, the results for each strategy generally show larger impacts than those obtained for the historical simulation. Concerning the impact of Strategy 1, a similar behaviour is observed among scenarios and time periods. For example, for 1000 MW, the impact is about 25-30% regardless of the mitigation scenario and the time period. The impact of Strategy 2 is more dependent on the scenario and the time period. During the beginning of the century, the scenarios' curves overlap with that of the historical period. However, for the middle and end of the century, the impact becomes more pronounced, especially for RCP 8.5, with a larger reduction of wildfires compared to the historical period. For instance, at 100 MW, the impact rises from 15% to more than 20%, at 1000 MW, it increases from 40% to 50%, and for very large values of log10(FRP), it escalates from 65% to more than 75%.

Finally, the impact of Strategy 3 reveals to be the most sensitive to mitigation scenarios and time periods. As for Strategies 1 and 2, during the beginning of the century, there were very small differences between scenarios and historical simulation. However, for RCP 8.5 in the middle and end of the century, as well as for RCP 2.6 in the middle and RCP 4.5 at the end of the century, there is a strong impact in the reduction of wildfires, reaching more than 60% for RCP 8.5 by the end of the century for very high values of log10(FRP) (compared to below 50% in the historical period).

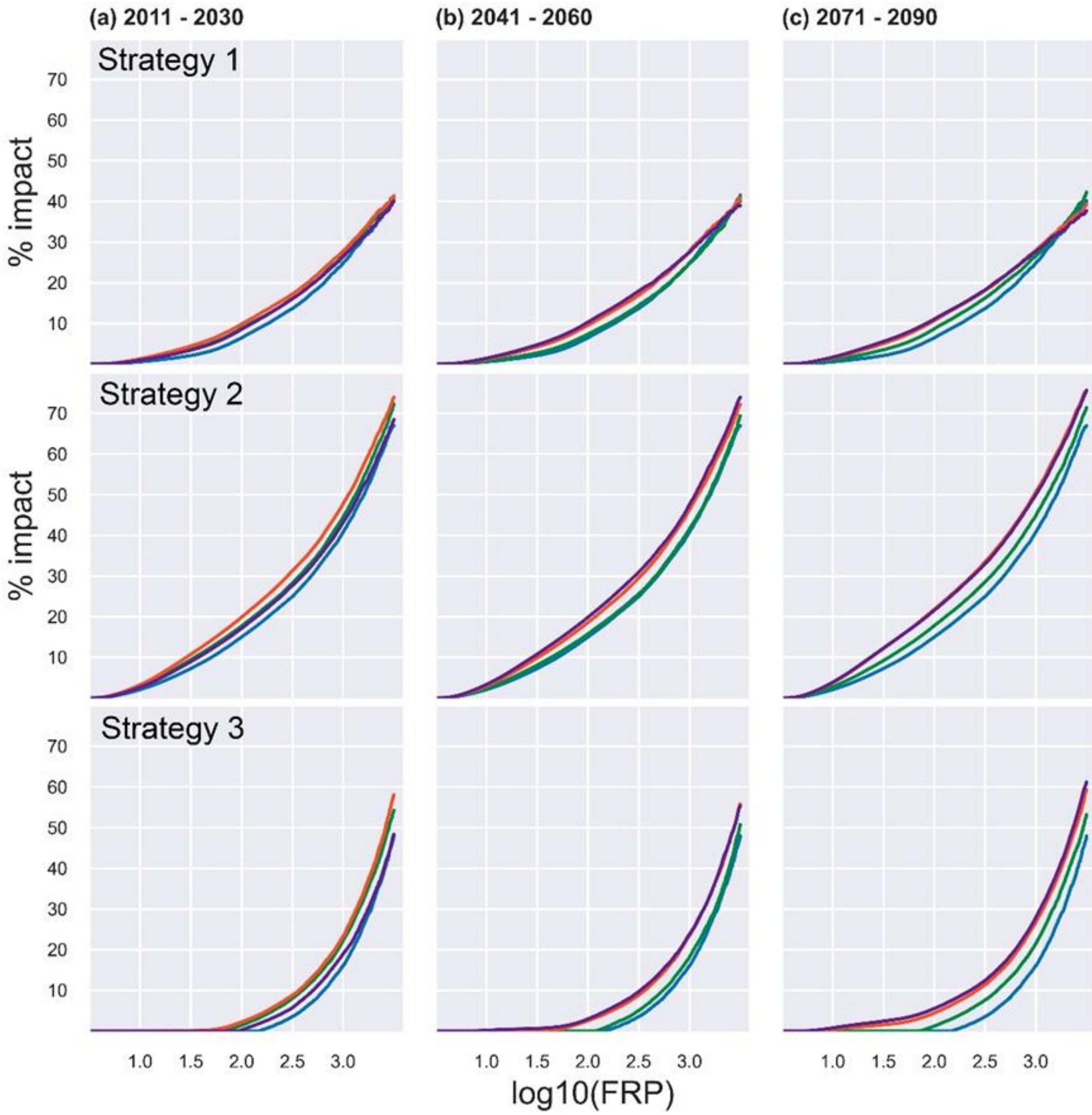


Figure 3.2.4 – Impact on log10(FRP) on vegetation fire hotspots for three different adaptation strategies. Results for the historical period (blue line) and the projected scenarios RCP 2.6 (green line), RCP 4.5 (orange line), and RCP 8.5 (red line) for the three 20-year future periods 2011 – 2030 (a), 2041 – 2060 (b), and 2071 – 2090 (c).

These findings call for urgent and effective fire prevention strategies aiming to attenuate the potential impact of climate change on wildfire occurrences. Even with ambitious efforts to reduce emissions (RCP 2.6), the risk of encountering highly energetic wildfires remains a significant concern. The continuous increase in FRP probabilities under more severe emission scenarios (RCP 4.5 and RCP 8.5) highlights the pressing need for comprehensive and adaptive wildfire management strategies to safeguard communities and ecosystems in the face of escalating fire risks.

Here, we considered three adaptation strategies of fire prevention and analysed their impacts on fire behaviour, which may be summarised as:

1) **Strategy 1**, involving a random reduction of 50% of FRPs when FWI exceeds the sample median, showcased appreciable reductions in the probability of exceedance of log10(FRP) across all energy thresholds. Notably, fires with an energy release of 100 MW showed a decrease of about 10%, whereas those with 1000 MW and very high log10(FRP) revealed reductions of about 25% and 40%, respectively. This strategy showed to be promising to curb fire occurrences in moderate fire weather conditions, however it does not deal very effectively with the most intense fires. Moreover, this strategy implies that some type of warning system and implementation strategy must be applied to a rather large number of days and regions with moderate fire danger, with high costs at the level of both resources and manpower;
2) **Strategy 2**, where 50%, 90%, and 95% of log10(FRP) were randomly reduced for FWI ranging between the 75th and 90th sample percentiles, 90th and 95th sample percentiles, and above 95th sample percentile, respectively, the impact was more pronounced than in Strategy 1. The probability of exceedance decreased by approximately 15%, 40%, and 70% for 100 MW, 1000 MW, and very large FRP, respectively. This strategy's targeted approach exhibited the potential to significantly decrease the occurrence of fires in regions experiencing extreme fire weather conditions;
3) **Strategy 3**, involving the random reduction of 95% of FRPs when FWI exceeded the 95th sample percentile. Although showing smaller reductions when compared to Strategy 2, with decreases of around 0%, 20%, and 50% for 100 MW, 1000 MW, and maximum FRP, Strategy 3 proved effective in reducing the occurrence of extremely intense fires during the most critical fire weather conditions and may lead to less but more focused resources.

It should be noted that the impacts of Strategy 2 are higher than those of the other two, both for historical and future scenarios. However, this strategy is clearly more difficult to implement due to the different levels of reduction, which would need a rather complex infrastructure of warning systems and resources applied to a larger number of areas and days. **Strategy 3 is therefore the one that seems more promising because it addresses the increasing challenges posed by extreme fire weather events under climate change scenarios, while significantly reducing the number of times when these measures are implemented. In fact, its effectiveness in mitigating ignitions during extreme fire weather events makes it a valuable tool in reducing the probability of occurrence of highly intense fires in Portugal.** By prioritizing Strategy 3, wildfire management can adopt a proactive and adaptive approach, significantly reducing the need for stringent authoritative actions during the summer while ensuring the protection of communities and ecosystems from the escalating threat of extremely energetic fires.

We acknowledge that this study is not without its limitations, and some caveats need to be considered when interpreting the results. The first limitation pertains to the assumption of static vegetation in the future projections. By assuming that the same areas that experienced wildfires during the historical period of 2001–2020 will remain unchanged in the future, we overlook the potential impact of climate change on vegetation structure (Bento et al., 2021; Nolan et al., 2021; Seidl et al., 2017). Adaptation strategies to climate change may involve altering the landscape's vegetation (Chausson et al., 2020), and as aridity increases in the region (Andrade et al., 2021), the types of vegetation might naturally shift.

These strategies may be directly linked to concrete adaptation measures (please refer to WP1 stakeholder engagement report). Drawing upon insights gathered from discussions with experts and specialists in the field, we have consolidated their knowledge and expertise to formulate the following adaptation measures to achieve each above-mentioned strategy:

1) **Strategy 1**: Reducing ignitions through awareness campaigns and settling the population in rural areas. These two measures may lead to less ignitions during moderate fire weather conditions. However, it is crucial to understand that changing the mentality and the geographical base of the population is not achievable in a short period of time. Let’s call it Awareness strategy,
2) **Strategy 2**: Increasing response capacity in wildfire situations. This adaptation measure may be a way to achieve the threshold-based Strategy 2. However, since the strategies are developed to reduce ignitions, the increased response capacity should be to prevent those from happening. The strategy requires a growing number of authorities depending on the threshold of fire weather conditions. Let’s call it Awareness + Coercive strategy.
3) **Strategy 3**: Strict and focused (in time and space) state of emergency declaration (objective emergency system with local criteria). Strategy 3 addresses ignitions that have a larger probability of resulting in mega-fires, acting only in the very extreme days of fire weather. Let’s call it Coercive strategy.

In summary, this study explores three distinct fire prevention adaptation strategies and their associated measures to achieve reductions in ignitions and mitigate the impact of wildfires under changing climate conditions. While Strategy 2 shows higher impacts, its complexity in implementation may pose challenges. Strategy 3 is deemed promising, effectively addressing extreme fire weather events while reducing the frequency of implementation. Recommendations for Stakeholders and Policymakers are:

- Recognize the effectiveness of Strategy 3 in addressing challenges posed by extreme fire weather events.
- Prioritise long-term efforts in implementing Strategy 1 measures, considering the challenges of changing population mentality and geography.
- Consider the potential complexities of Strategy 2 implementation, requiring a sophisticated infrastructure of warning systems and resources.

This consolidated summary aims to inform stakeholders and policymakers about the efficacy of the presented adaptation strategies and measures, providing valuable insights for decision-making in wildfire management and climate resilience.

3.2.3. Adaptation costs

In recent decades, the global climate has undergone unprecedented changes, with rising temperatures, altered precipitation patterns, and more frequent extreme weather events becoming increasingly evident. Among the most pressing consequences of this shift is the escalation in the frequency and intensity of forest fires. As these fires ravage landscapes worldwide, they exact a heavy toll not only on ecosystems but also on human communities, economies, and public health.

This report delves into the intricate nexus between climate change and the escalating costs associated with adapting to forest fires. As temperatures soar and precipitation patterns fluctuate, forests are experiencing prolonged periods of drought and heightened vulnerability to ignition, creating optimal conditions for the rapid spread of wildfires. The implications of these fires extend far beyond the immediate areas of impact, triggering cascading consequences that reverberate across regional and global scales.

While the ecological devastation wrought by forest fires is evident, the economic ramifications are equally profound. From direct firefighting expenditures to indirect costs such as loss of property, infrastructure damage, and healthcare expenses, the financial burden of forest fires is staggering. Moreover, the long-term effects, including diminished ecosystem services, reduced carbon sequestration capacity, and impaired water quality, impose additional hidden costs that exacerbate the economic strain.

Against this backdrop, understanding the economic dimensions of climate change adaptation in the context of forest fires is imperative for policymakers, stakeholders, and communities alike. By elucidating the underlying factors driving adaptation costs, identifying cost-effective mitigation strategies, and exploring innovative financing mechanisms, this report aims to inform evidence-based decision-making and foster resilience in the face of escalating climate risks.

Through a comprehensive analysis of empirical data, case studies, and expert insights, this report seeks to shed light on the multifaceted challenges posed by forest fires in the era of climate change. By quantifying the economic impacts of adaptation measures and exploring pathways for sustainable management, it endeavours to catalyse proactive interventions that mitigate risks, safeguard ecosystems, and protect livelihoods. In doing so, we endeavour to pave the way for a more resilient and sustainable future in the face of mounting climate challenges.

The cost of doing nothing is estimated for each NUTS II by assuming a cost of wildfire by unit of ha. Unfortunately, there is no extended information on the real value lost due to wildfires. Hence, we took the values known from some events and divided by the burnt area associated with that event. Table 3.2.1 shows the 5 selected events.

Table 3.2.1 – Selected events for each NUTS II where the burned area and cost is known.

	Location	Year	Burned Area (ha)	Cost (million euros)
Norte	Picões	2013	15 000	13
Centro	Serra da Estrela	2022	26 619	35
AML	Palmela	2022	415	0.16
Alentejo	Odemira	2023	8 400	10
Algarve	Monchique	2018	27 000	2.1

Then, a value per unit of ha is assumed for each region and is multiplied by the total burnt area of the period 2003 – 2022 (Table 3.2.2).

Table 3.2.2 – Each NUTS II total burnt area 2003 – 2022, and total monetary cost associated to it.

	Total Burned Area (2003 – 2022)	Cost per ha (euro)	Total cost (2003 – 2022) (million euros)
Norte	1002869.5	866.67	869.2
Centro	1303255.8	1314.85	1713.6
AML	22844.6	380.72	8.7
Alentejo	276856.0	1190.48	329.6
Algarve	182067.2	77.78	14.1

Taking into account that most burned area is due to the larger wildfires, we selected the probability of having wildfires with more than 1000 MW in the future, as described in WP4. Hence, for each NUTS II, the total burned area is multiplied by that probability and then by the cost per ha. This allows to have an estimated cost extrapolated into the different future periods and scenarios. Table 3.2.3 displays those values divided by 20 years, i.e., the cost per year.

Table 3.2.3 – Each NUTS II cost without adaptation.

	2011 – 2030	2041 – 2060	2071 – 2090
		Norte	
RCP 2.6	70 618 727.29 €	80 396 704.92 €	64 100 075.54 €
RCP 4.5	58 667 865.75 €	82 569 588.83 €	82 569 588.83 €
RCP 8.5	63 013 633.58 €	89 088 240.58 €	112 989 963.67 €
		Centro	
RCP 2.6	139 228 884.68 €	158 506 730.25 €	126 376 987.63 €
RCP 4.5	115 667 073.42 €	162 790 695.93 €	162 790 695.93 €
RCP 8.5	124 235 004.79 €	175 642 592.98 €	222 766 215.49 €
		AMLisboa	
RCP 2.6	706 668.80 €	804 515.25 €	641 437.83 €
RCP 4.5	587 078.70 €	826 258.91 €	826 258.91 €
RCP 8.5	630 566.01 €	891 489.87 €	1 130 670.08 €
		Alentejo	
RCP 2.6	26 779 226.19 €	30 487 119.05 €	24 307 297.62 €
RCP 4.5	22 247 357.14 €	31 311 095.24 €	31 311 095.24 €
RCP 8.5	23 895 309.52 €	33 783 023.81 €	42 846 761.90 €
		Algarve	
RCP 2.6	1 150 563.56 €	1 309 872.36 €	1 044 357.69 €
RCP 4.5	955 852.80 €	1 345 274.31 €	1 345 274.31 €
RCP 8.5	1 026 656.71 €	1 451 480.18 €	1 840 901.69 €

Following the three adaptation strategies previously discussed it is possible to reduce ignitions and thus burned area and consequently the overall cost per year. **Table 3.2.4** shows the cost when adaptation is followed.

Table 3.2.4 – Costs (€) with adaptation strategies S1: Awareness; S2: Awareness + Coercive; S3: Coercive.

	2011 – 2030			2041 – 2060			2071 – 2090		
	S1	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
					Norte				
RCP 2.6	45 902 172.74	30 366 052.74	45 902 172.74	53 865 792.29	34 570 583.11	52 257 858.20	42 947 050.61	27 563 032.48	40 383 047.59
RCP 4.5	38 134 112.74	23 467 146.30	34 027 362.14	53 670 232.74	33 027 835.53	49 541 753.30	53 670 232.74	30 550 747.87	45 413 273.86
RCP 8.5	40 958 861.83	28 356 135.11	40 958 861.83	57 907 356.38	35 635 296.23	53 452 944.35	73 443 476.38	41 806 286.56	62 144 480.02
					Centro				
RCP 2.6	90 498 775.04	59 868 420.41	90 498 775.04	93 283 352.73	59 868 420.41	90 498 775.04	93 283 352.73	59 868 420.41	87 714 197.35
RCP 4.5	75 183 597.73	46 266 829.37	67 086 902.59	75 183 597.73	46 266 829.37	69 400 244.05	75 183 597.73	42 796 817.17	63 616 890.38
RCP 8.5	80 752 753.11	55 905 752.16	80 752 753.11	80 752 753.11	49 694 001.92	74 541 002.87	80 752 753.11	45 966 951.77	68 329 252.63
					AMLisboa				
RCP 2.6	459 334.72	303 867.58	459 334.72	539 025.22	345 941.56	522 934.91	429 763.35	275 818.27	404 105.84
RCP 4.5	381 601.15	234 831.48	340 505.64	537 068.29	330 503.56	495 755.34	537 068.29	305 715.80	454 442.40
RCP 8.5	409 867.90	283 754.70	409 867.90	579 468.42	356 595.95	534 893.92	734 935.55	418 347.93	621 868.55
					Alentejo				
RCP 2.6	17 406 497.02	11 515 067.26	17 406 497.02	20 426 369.76	13 109 461.19	19 816 627.38	16 285 889.40	10 452 137.98	15 313 597.50
RCP 4.5	14 460 782.14	8 898 942.86	12 903 467.14	20 352 211.90	12 524 438.10	18 786 657.14	20 352 211.90	11 585 105.24	17 221 102.38
RCP 8.5	15 531 951.19	10 752 889.29	15 531 951.19	21 958 965.48	13 513 209.52	20 269 814.29	27 850 395.24	15 853 301.90	23 565 719.05
					Algarve				
RCP 2.6	747 866.31	494 742.33	747 866.31	877 614.48	563 245.11	851 417.03	699 719.65	449 073.81	657 945.34
RCP 4.5	621 304.32	382 341.12	554 394.62	874 428.30	538 109.72	807 164.59	874 428.30	497 751.50	739 900.87
RCP 8.5	667 326.86	461 995.52	667 326.86	943 462.12	580 592.07	870 888.11	1 196 586.10	681 133.62	1 012 495.93

3.3. Coastal Areas

Adaptation to climate change is one of the greatest challenges of our time, especially in coastal areas, a zone exposed to the majority of its related impacts. These impacts encompass retreating coastlines which is linked to sea level rise (SLR), accelerated erosion, an increase in the intensity of storms, saltwater intrusion as well as the degradation of marine and coastal ecosystems. The second part of the 6th IPCC report, released in 2022 and which deals with the vulnerability to climate change and adaptation measures, estimates that coastal territories will be increasingly sensitive and exposed to chronic flooding and storms between now and 2050 and, in the longer term (2050 to 2150), to an increase in salinization, erosion and permanent flooding. The effects of climate change will pose existential threats to islands, low-lying coastal areas and coastal cities, with associated risks for coastal communities and infrastructures. In order to minimise the impacts of climate change, it is essential to mitigate and adapt swiftly to these exceptional circumstances. This societal relevance was translated in the United Nation 2030 Sustainable Development Goals that stress the need for adaptation to climate change in the coastal zone:

- Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable
- Goal 13: Take urgent action to combat climate change and its impacts
- Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
- Goal 15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.

The 6th Assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) argues that the majority of the sandy coasts around the world will experience an increase in coastal erosion over the twenty-first century. An increase in long term coastal erosion (coastline recession) along sandy coasts can translate into massive socio-economic impacts, unless appropriate adaptation measures are implemented in the next few decades. Increasing coastal hazards combined with development and demographic concentration in coastal areas makes the need for adaptation urgent. To adequately inform adaptation measures, it is necessary to have a good understanding of the relative importance of the physical processes driving coastline recession, as well as of linkages between consideration (or not) of certain processes and the level of risk tolerance.

Coastal areas constitute one of the most heavily populated and developed land zones in the world. The combination of climate change impacts, declining fluvial sediment supply, and heavy human presence on the coastal areas will very likely lead to massive socio-economic and environmental losses in the coming decades. Effective coastal planning/management strategies that can help circumvent such losses require reliable local scale (<10 km) projections of coastal change resulting from the integrated effect of climate change driven variations in mean sea level, storm surge and waves impacts (Ranasinghe, 2020).

Adaptation approaches should consider different urban and economic settings. Furthermore, it is crucial to consider existing legal planning instruments in developing adaptation solutions as well as the effects of acceleration of climate change. It is most of all necessary to consider the different scenarios of sea level rise, which may constrain the necessary structural changes. Rather than a single strategy, the development of a hybrid response, that combines both natural options and infrastructure-based approaches, may allow for a more flexible and integrated protection of coasts enabling a better adaptation in the face of uncertainty. Therefore, coastal strategy plans should be tailored to the specific needs and vulnerabilities of each region, as the challenges and opportunities can vary widely depending on location. Nevertheless, effective adaptation to climate change requires a multi-faceted approach that combines both structural and non-structural measures, and it often involves a long-term commitment to building resilience in coastal environments and communities. Broadly speaking, coastal adaptation strategies rely on three main axis of action: protect, accommodate and retreat (Figure 3.3.1).

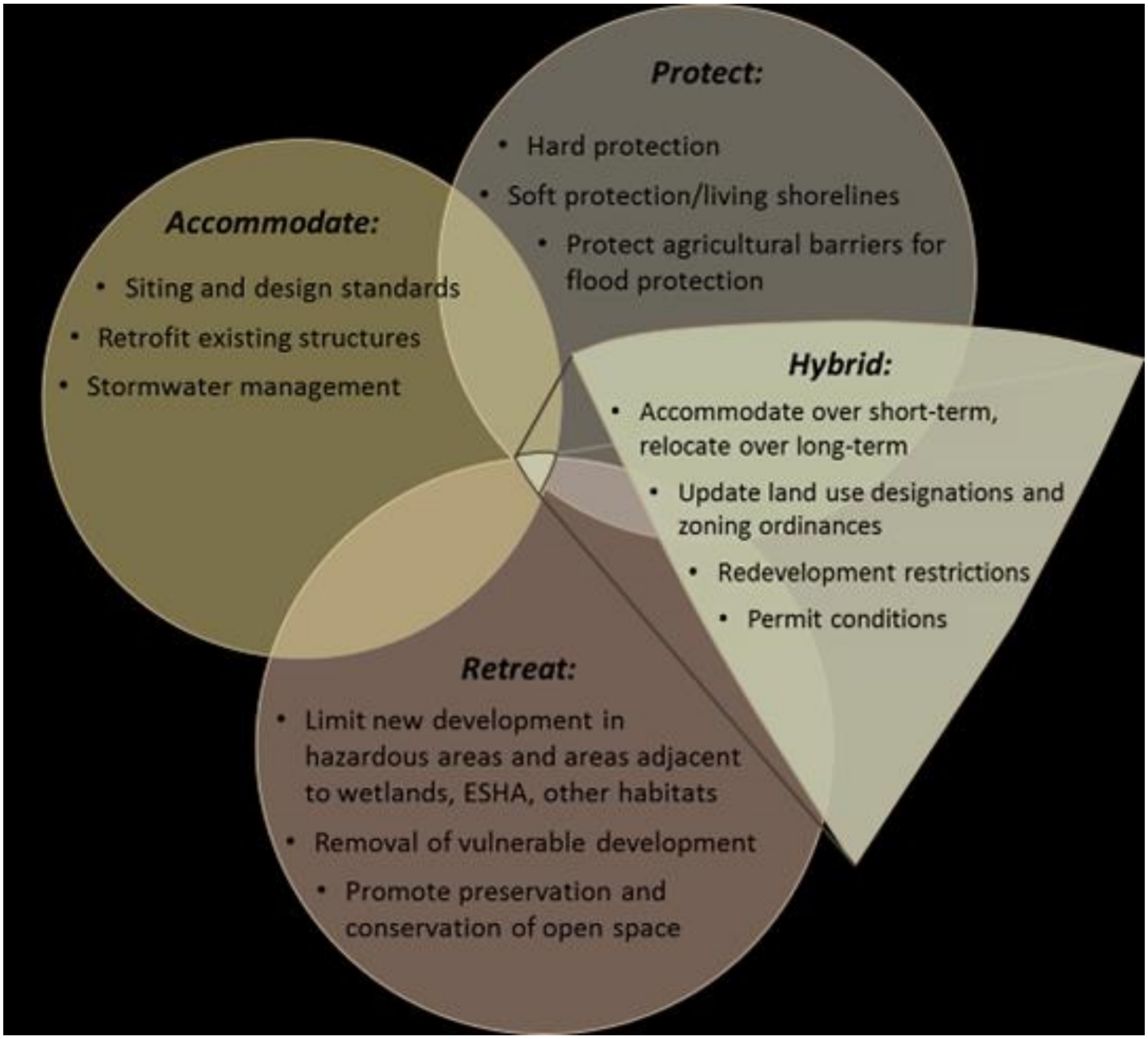


Figure 3.3.1 – Mean strategic axis to face coastal adaptation.

Coastal hazards, generally caused by synchronized extreme physical processes along the coast, can cause damage, disruption, and even casualties. Many of these risks are worsening due to climate change, most notably the continuous rise in sea level, which contributes to the increase in frequency and intensity of hazardous events. The characterization of risk associated with extreme coastal flooding along the Portuguese coastline is of paramount importance for efficient adaptation planning.

In this report, a thorough description of the socioeconomic impacts related to the occurrence of extreme physical events along the Portuguese coastlines in a changing climate is presented. In articulation with the results from WP4 (the reader is referred to the WP4.5/6 report on the physical impacts projected to be felt along the coastal areas), here, our goal is fourfold (Figure 3.3.2). First, the “no action” (or “inaction”) costs are quantified, considering the composed Coastal Vulnerability Index (CVI) obtained for the entire extension of the Portuguese (ocean-facing and inland-water) coastlines. The patrimonial value of urban buildings vulnerable to the physical impacts of climate change is used as a reference to probabilistically estimate the inaction costs at a national scale (considering a range of possibilities depending on the CVI level). Then, through a measure of exposure, here considered as the residents vulnerable to the physical impacts of climate change along the Portuguese coastlines (based on the CENSOS2021 data), the Exposure Vulnerability Index (EVI) is calculated, which, together with the CVI, allow to determine the risk through the Coastal Risk Index (CRI). The flowchart in Figure 3.3.2 details this approach. The third step consists of revealing and describing the proposed adaptation measures (in articulation with the WP1 stakeholder engagement report), identifying the most suitable locations for their implementation at a national scale. Finally, the adaptation costs are quantified, considering a large field dataset provided by the Portuguese Environment Agency ("*Agência Portuguesa do Ambiente*"; APA) for a set of grey and green infrastructure measures.

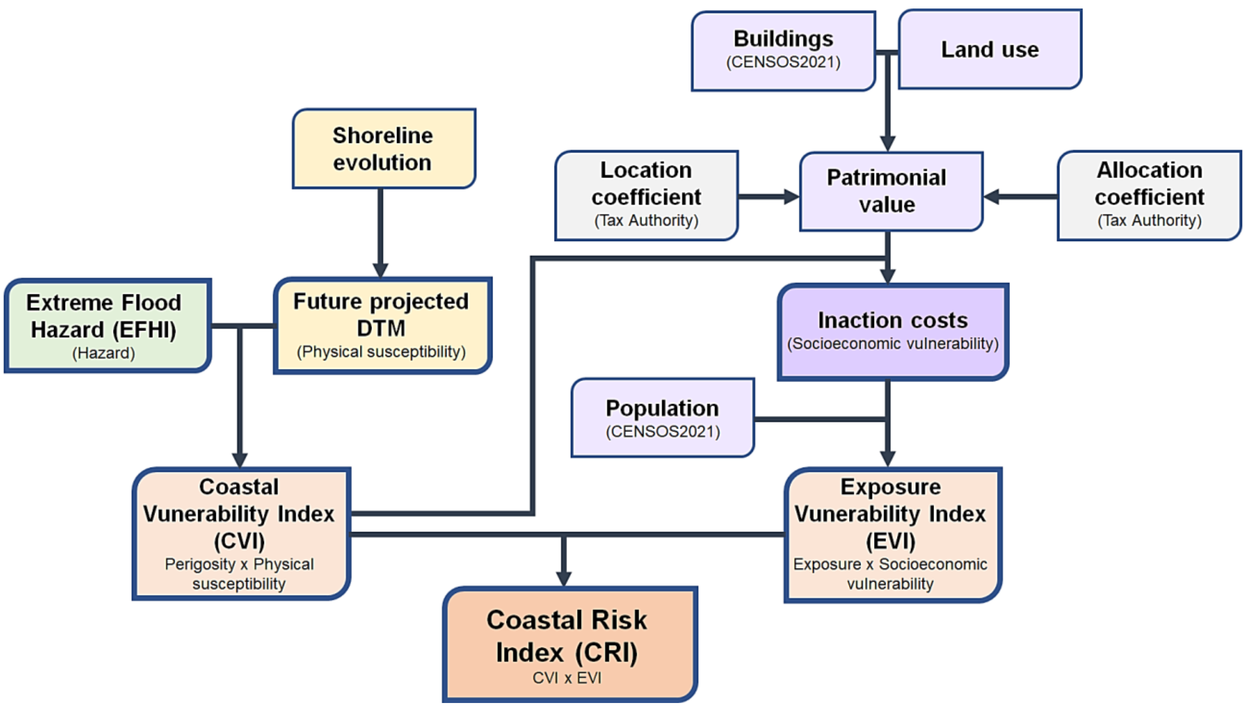


Figure 3.3.2 – Coastal vulnerability, exposure and risk assessment framework, considering the inaction (or "no action" economic costs).

3.3.1. Total Inaction Costs and Coastal Risk

Considering the results from the WP4 dynamical impact modelling report, overall, the inaction costs (or "no action" costs) are estimated by crossing the Coastal Vulnerability Index (CVI) cartography with the geographical distribution of patrimonial value related to buildings and land, using data from the CENSOS

2021, the Portuguese Tax Authority ("*Autoridade Tributária*"; AT), as well as reference values published in the Ordinances and Decrees-Law. The patrimonial value is obtained by crossing several fixed parameters of geographical value for urban buildings, with the location coefficient that escalates such values by location. The patrimonial value of the urban buildings laying currently inside the areas projected to be under CVI in the future is calculated, considering the three vulnerability levels (namely low, moderate and high). Finally, the sum of the vulnerable patrimonial values, at a national scale, under the three CVI levels, corresponds to the overall inaction costs, probabilistically estimated for the range of possible future extreme coastal flooding projections, with direct relationship with the 100-year (low), 25-year (medium) and 4-year (high) total water level (plus extreme waves for the ocean-facing coastlines) return periods.

The Coastal Risk Index (CRI) is given by the combination of the CVI and the Exposure Vulnerability Index (EVI). Similarly to the CVI, the CRI is normalized into three levels (low, moderate and high).

3.3.1.1. Introduction and framework

Along the Portuguese coastal areas, the Total Inaction Cost (TIC) is an estimate of costs and damages associated with the impacts of coastal erosion and flooding resulting from the TWL projections, considering the combination of SLR, tides and storm surges associated to three return periods, and the total runup of extreme waves, for a 99th energy percentile, through the three levels of Coastal Vulnerability Index (CVI; 1 – Low; 2 – Moderate; 3 – High).

The TIC calculation formula includes the costs countable through the Taxable Asset Value ("*Valor Patrimonial Tributável*"; VPT), estimated with spatial disaggregation at the level of each statistical subsection of the National Institute of Statistics ("*Instituto Nacional de Estatística*") – Geographic Information Reference Base (BGRI). Various geographic parameters are incorporated in the TIC, sourced from multiple authoritative entities. These include data provided by National Institute of Statistics, at the CENSOS level, the Location Coefficient from the Portuguese Tax Authority, as well as data from Ordinances and Decrees-Law, officially published in the Republic's official journal ("*Diário da República*"; DR).

As it is demonstrated in the methodology, the recession of the Margin Limit that legally defines the Public Maritime Domain ("*Domínio Público Marítimo*"; DPM) may account for a considerable portion of the TIC, nevertheless, given the unfeasibility to correctly compute the exact area that is converted from private to public domain in the CVI scenarios, it is not possible to account for such costs.

Direct costs related with damages of critical infrastructure, including harbours, encompassing commercial, recreational, and fishing facilities, alongside other hinterland port infrastructure, are not considered for this assessment. Other indirect costs related to the loss of economic activities, as tourism and employment, are not also considered into this assessment. Furthermore, the costs associated with disruptions in the supply chain of material and goods through maritime transport, both at the foreland and hinterland level, resulting from maintenance and protection interventions of port infrastructures, are also challenging to materialize.

Similarly to the remaining study components under analysis, the TIC is estimated considering an adjusted value for the year of 2023, without any adjustment for inflation or macroeconomic projections for the future periods. For the purposes of this analysis, the user must consider that the real inaction costs, both direct and indirect, can be substantially higher, in nominal value, than the ones presented here, assuming a scenario of economic growth throughout the 21st century.

3.3.1.2. Methodology

The TIC is based on the VPT, considering four assumptions:

1) The Base Value of buildings for 2023, defined by Ordinance No. 7-A/2023, is 532€/m^2 (133€/m^2 for land value, corresponding to 25% of the Base Value, and 665€/m^2 for buildings, corresponding to the addition of the Base Value to the land value). This value is the basis to determine the VPT of the coastal areas under CVI.
2) The median value of sales, per square meter, of family housing in the last 12 months, calculated by INE in the 3rd quarter of 2023, is 1541€/m^2. This value corresponds to an average increase factor (FM) of 2.3, compared to the Base Value of Ordinance No. 7-A/2023. Given that INE estimates the family housing values at the NUTS I and II levels, and by municipalities, it is possible to differentiate the respective FM for each municipality and convert the Base Value into a unitary asset value with geographic disaggregation along the entire coast of Portugal Mainland.
3) Associated with the urbanization there are municipal charges for Building and Urban Planning, associated with complementary infrastructure and services (roads and streets, parking, electrical and public lighting networks, sanitation, water, gas and telecommunications networks, and other complementary urban equipment), both in terms of implementation and maintenance. In the absence of a reference, a value of 10% of the VPT is applied, which results in the Urban Cost Factor (FEU) based on Municipal Regulations for determining Urban Fees and Charges, coinciding with the one established for evaluation purposes in the Code of Expropriations.

4) The estimated value of the IMI (Municipal Property Tax) for buildings within the areas projected to become under CVI, leading to potential revenue loss (among other taxes), is included. This contributes to the TIC, with a taxation period calculated as 23 years (30 years minus the 7-year exemption for first homes). It is computed by housing area using the rates of taxable values by municipality published by AT.

With the FM given by assumption 2), the aim is to convert the VPT into real estate asset value – VTI (of housing and land). And with the FEU, from assumption 3), the aim is to add to the TIC the unaccounted value of buildability and urbanization costs in the VTI. While the IMT (Municipal Tax on Onerous Property Transfers) could also be considered, since it varies between just 2% to 8% of the VPT at the time of the transaction and there is still a portion to be deducted, the real IMT value in this context would be insignificant (less than 1%).

Considering SLR, the boundary of CVI Level 3 (representing the limit of a 4-year return period coastal flooding event) will align, most likely, with the projected future LMPAVE (line of the equinoctial high water maximum level). This will consequently establish the maritime Bed Line or Margin Line. Therefore, the limit of the DPM (50 m strip from the Bed Line or Margin) will undergo a retreat inland, converting part of the private domain of coastal areas and estuarine banks into public domain. Thus, in a future scenario, the DPM range that does not intersect the CVI area, will entail an additional cost to the TIC. This cost is estimated at 133€/m^2, representing the land value that becomes non-negotiable. Given the complexity of defining the DPM limit, both in the present context and for future scenarios of coastal flooding, particularly on the margins of the inland waters of estuaries and lagoon systems, this cost is not integrated into the current assessment. Nevertheless, simulations made at the municipality level show that this cost parcel might be considerable, in the context of the TIC.

The TIC, as of 2023, can be defined by the interval, between a minimum and a maximum:

$$TICmin = FM * DPP$$

$$TICmax = FM * DTP$$

The TIC minimum ($TICmin$) value is determined by the Partial Weighted Damage (DPP), which is calculated based on the assumption that there will not be a complete loss of the property's asset value, but rather a devaluation, depending on the level of vulnerability where the building is located. The TIC maximum ($TICmax$) value is given by the Total Weighted Damage (DTP) corresponding to the total loss of the property's asset value.

The Weighted Damage corresponds to the VPT, weighted by the percentage of the Vulnerable Area (AV) in relation to the total area of the statistical subsection (BGRI). This damage value can vary between a minimum limit, given by a partial value (DPP), and the maximum limit, given by the total value (DTP), of the Absolute Damage (DA) of the fraction of vulnerable land.

The Weighted Partial Damage (minimum value) is given by:

$$DPP = D_A * \left(\frac{\frac{1}{4} * AV(n1) + \frac{1}{2} * AV\ (n2) + 1 * AV\ (n3)}{ATotal} \right)$$

and the Total Weighted Damage (maximum value equal to the VPT of the vulnerable fraction) is given by:

$$DTP = D_A * \frac{AVtotal}{ATotal} = D_A * \left(\frac{AV(n1) + AV\ (n2) + AV\ (n3)}{ATotal} \right)$$

with the Absolute Damage (D_A) being:

$$D_A = VPT + \big(FEU(\%) + 23IMI(\%)\big) * VPT$$

$$D_A = VPT * (1 + TaxFEU + 23TaxIMI)$$

and the VPT:

$$VPT = V * A * C_{\mathrm{A}} * C_{\mathrm{L}} * C_{\mathrm{V}}$$

where:

- V is the Base Value of built buildings, defined in the national standard CIMI 2023, given in Ordinance No. 7-A/2023, as the value per square meter of buildings: 532€/m^2 + 25% x 532€/m^2 = 665€/m^2, and the value per square meter of land: 25% x 532€/m^2 = 133€/m^2.
- A is the Gross Construction, for land: A = Average Land Area, for buildings = Average Living Area x Number of Accommodations, with the Average Living Area being obtained from INE data, equal to an average of 112.4 m^2, and the Number of Accommodations being obtained for each BGRI from the CENSOS 2021.
- C_{A} is the Affectation Coefficient, defined in Art. 41 of Decree-Law No. 287/2003, of November 12th, according to affectation determined with the CENSOS 2021, in which, each BGRI is classified as housing, mixed or land.

- C_L is the Location Coefficient, obtained from AT, using the respective section value that corresponds to the type of BGRI affectation.
- C_V is the Age Coefficient, tabulated in Art. 44 Decree-Law No. 287/2003, of November 12th, being calculated using the average age of buildings in each BGRI.

Regarding coastal risk, assessments commonly consider it as a function of Physical Vulnerability and Exposure, being the Exposure a function of Damage (or Cost) and Socioeconomical Vulnerability, given through the Exposure Vulnerability Index (EVI; Figure 3.3.2). Here, the Physical Vulnerability is depicted through the CVI, while the EVI can be defined as a function of the TIC (representing the damage - economic costs), and the demographic analysis (quantified by the number of residents directly affected by coastal flooding). The number of residents, as well as the number of buildings, projected to be directly affected by coastal flooding in the future, correspond to the residents and buildings within the areas under CVI. The CENSOS 2021 provides data of residents and buildings (or the number of apartments/accommodation) by BGRI, essential for calculating the TICs and pursuing the risk assessment.

The EVI is obtained at each BGRI, combining the TIC and the demographic analysis (number of residents) through a geometrical average, overweighting the TIC. As both the TIC and number of residents are normalized into three level indexes to accomplish this task, the Coastal Risk Index (CRI) is therefore given by three levels as well, similar to the CVI (1 – Low; 2 – Moderate; 3 – High).

3.3.1.3. Demographic analysis and Total Inaction Costs (TICs)

The demographic analysis (number of residents projected to become under CVI in the future), according to the CENSOS 2021, by districts and municipalities, is shown in Figure 3.3.3 to Figure 3.3.10, respectively, considering the 2041-2070 and 2071-2100 periods under the RCP4.5 and RCP8.5 scenarios.

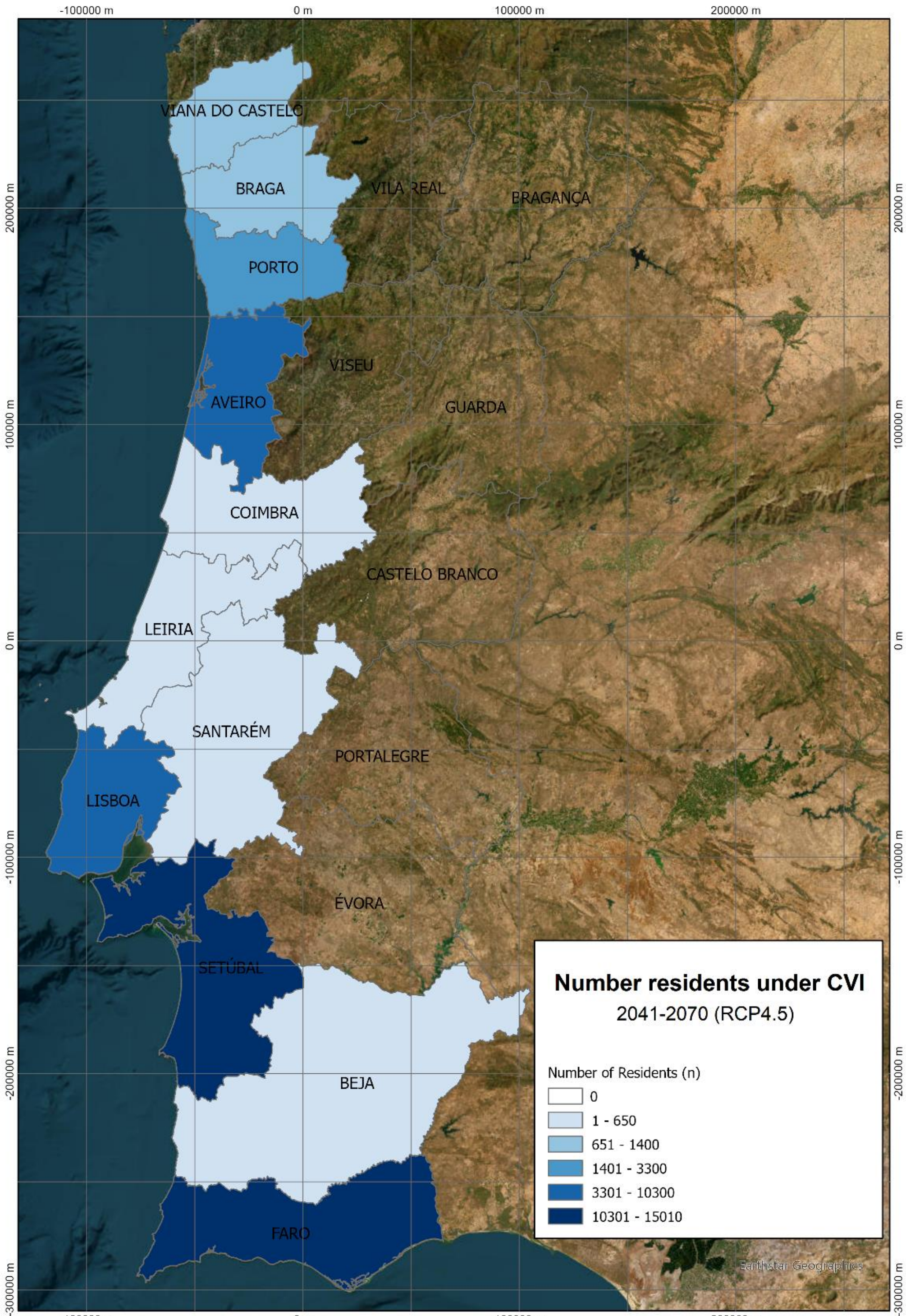


Figure 3.3.3 – Demographic analysis, expressed by the number of residents projected to become under CVI in the future (by the end of the 2041-2070 period, under RCP4.5), according to the CENSOS 2021, by districts of Mainland Portugal. Note that the color scale intervals are not uniform, being divided by quantiles (0%, 1-20%, 21-40%, 41-60%, 61-80% and 81-100%) considering the national range of values.

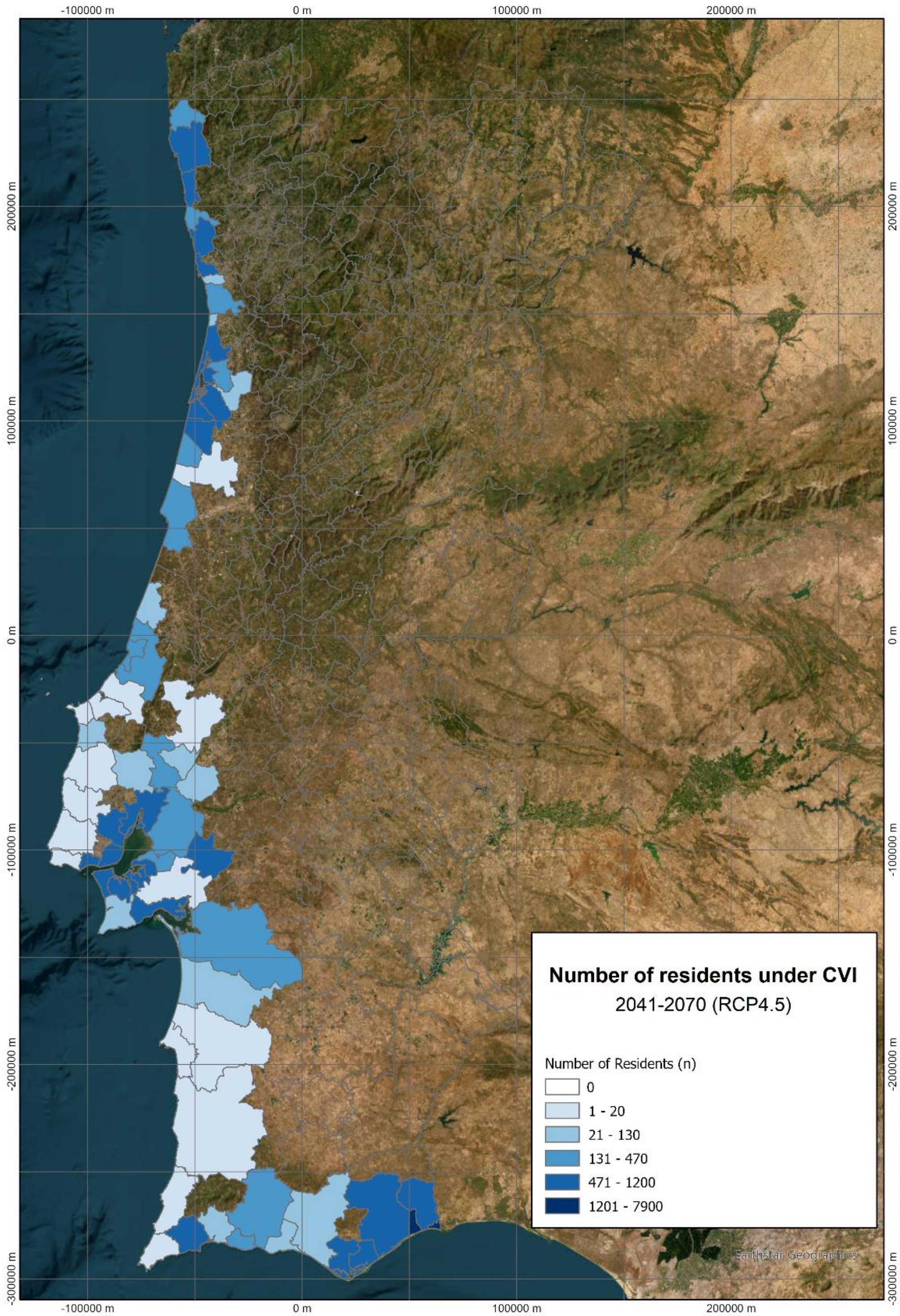


Figure 3.3.4 – Demographic analysis, expressed by the number of residents projected to become under CVI in the future (by the end of the 2041-2070 period, under RCP4.5), according to the CENSOS 2021, by municipalities of Mainland Portugal. Note that the color scale intervals are not uniform, being divided by quantiles (0%, 1-20%, 21-40%, 41-60%, 61-80% and 81-100%) considering the national range of values.

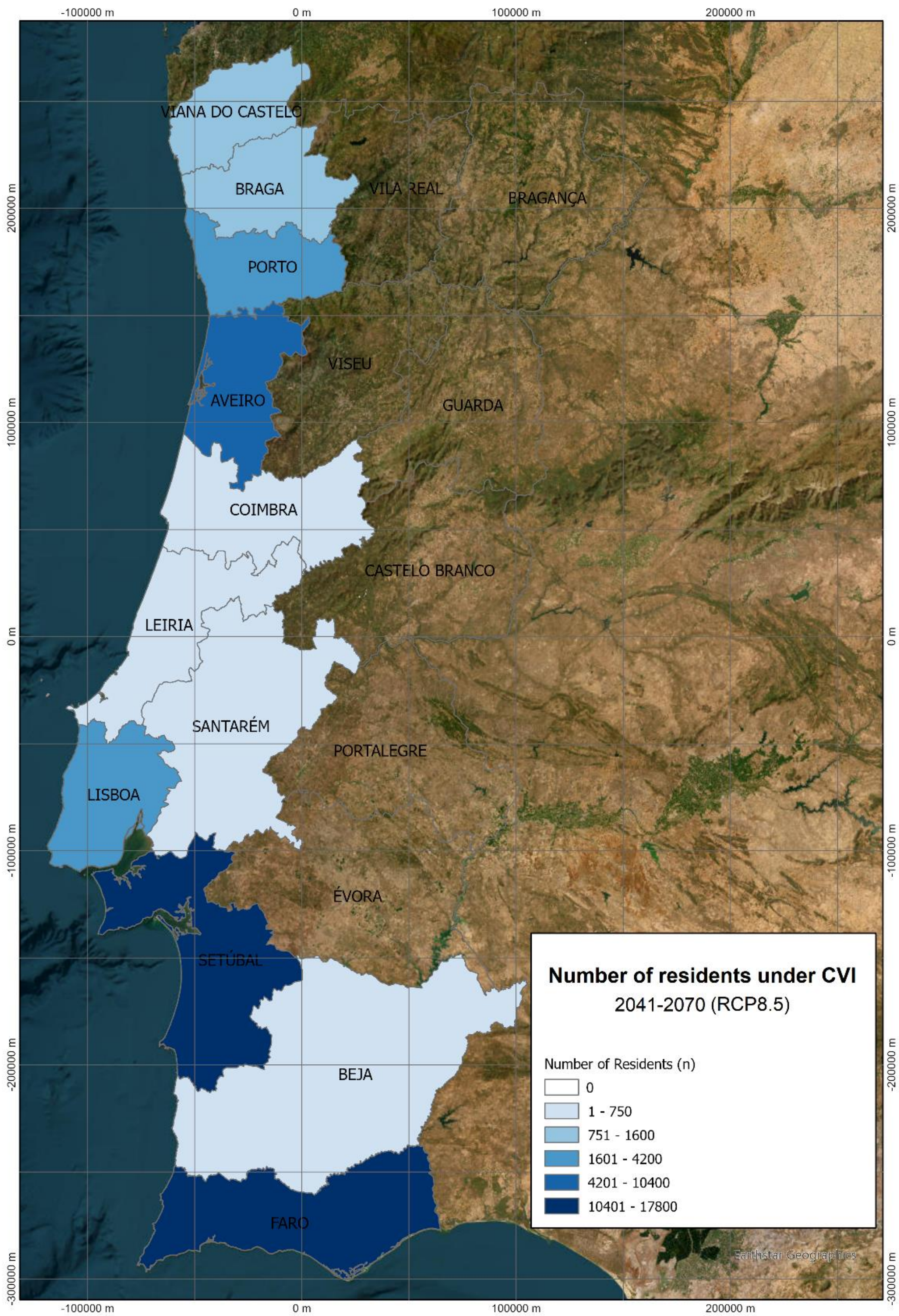


Figure 3.3.5 – Same as in Fig. 3.3.3, but for the RCP8.5 scenario.

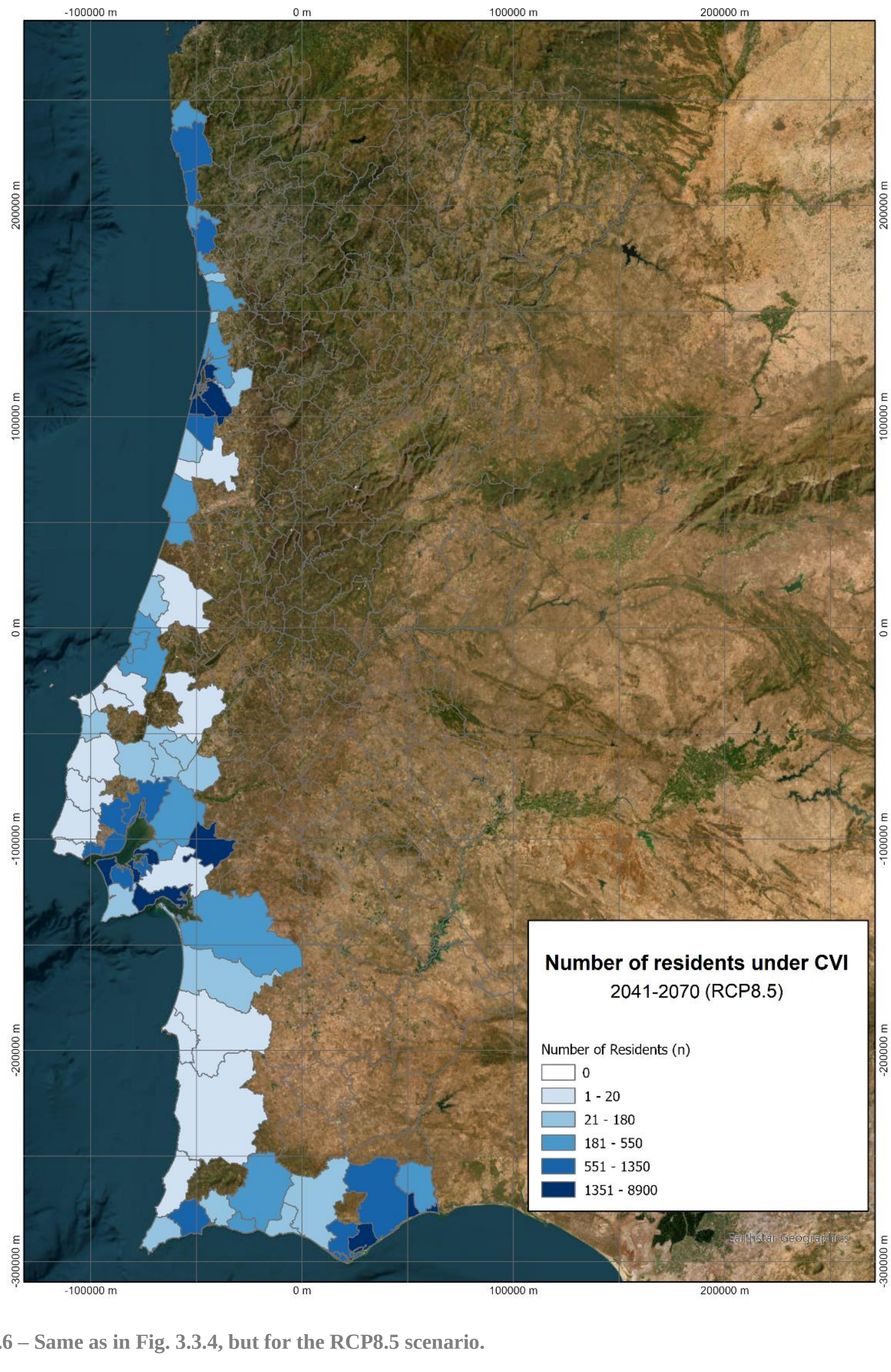


Figure 3.3.6 – Same as in Fig. 3.3.4, but for the RCP8.5 scenario.

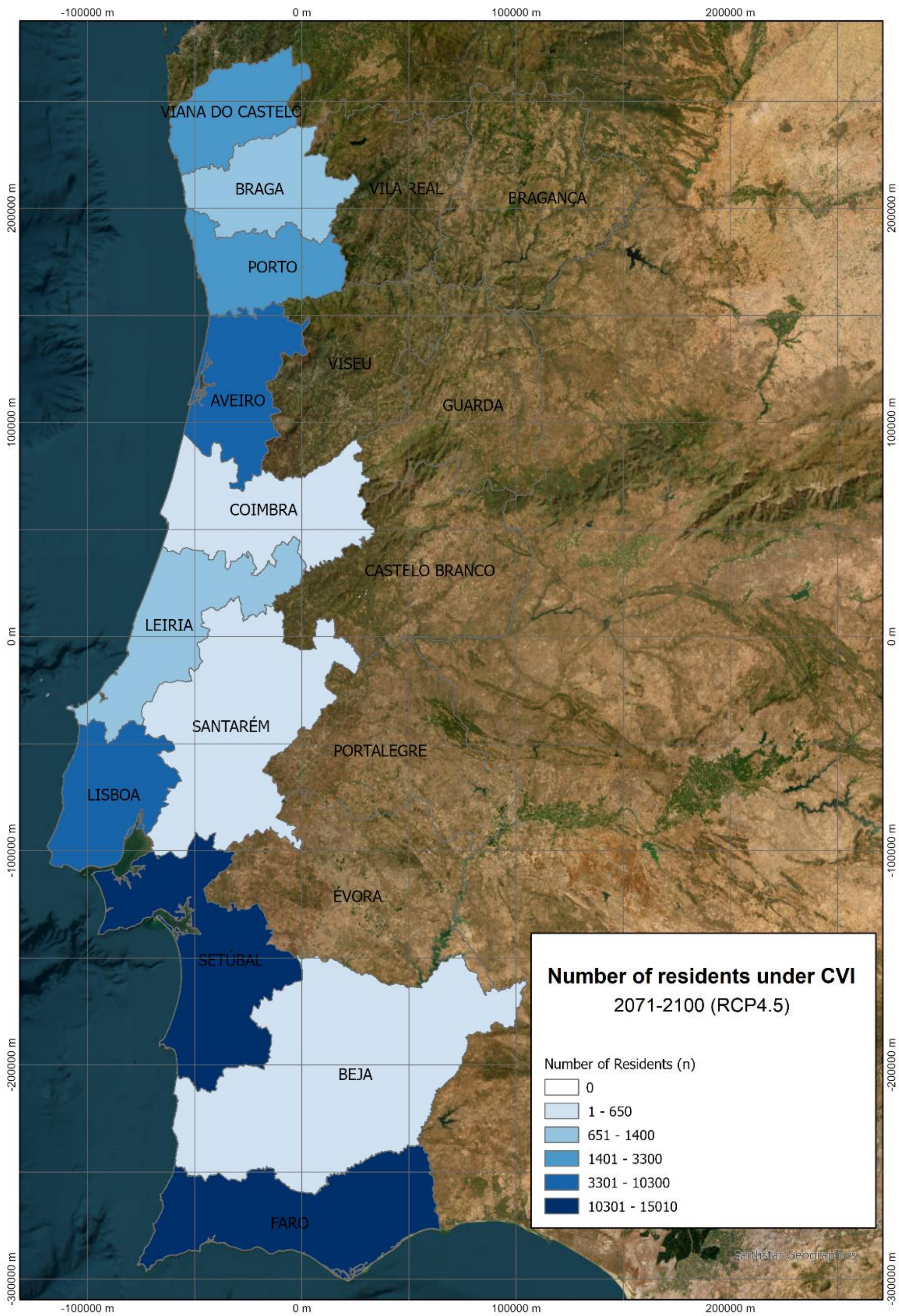


Figure 3.3.7 – Same as in Fig. 3.3.3, but by the end of the 2071-2100 period under the RCP4.5 scenario.

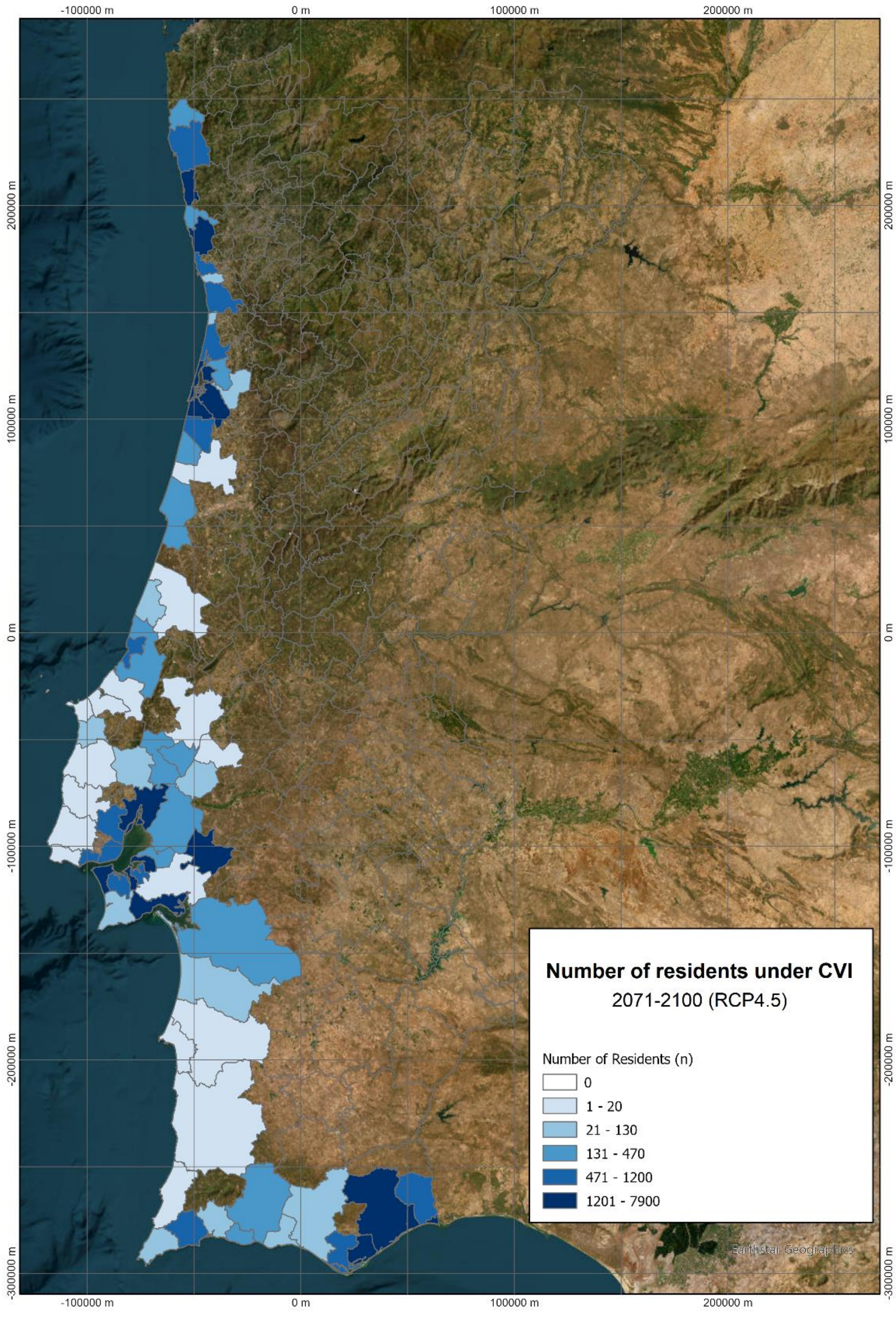


Figure 3.3.8 – Same as in Fig. 3.3.4, but by the end of the 2071-2100 period under the RCP4.5 scenario.

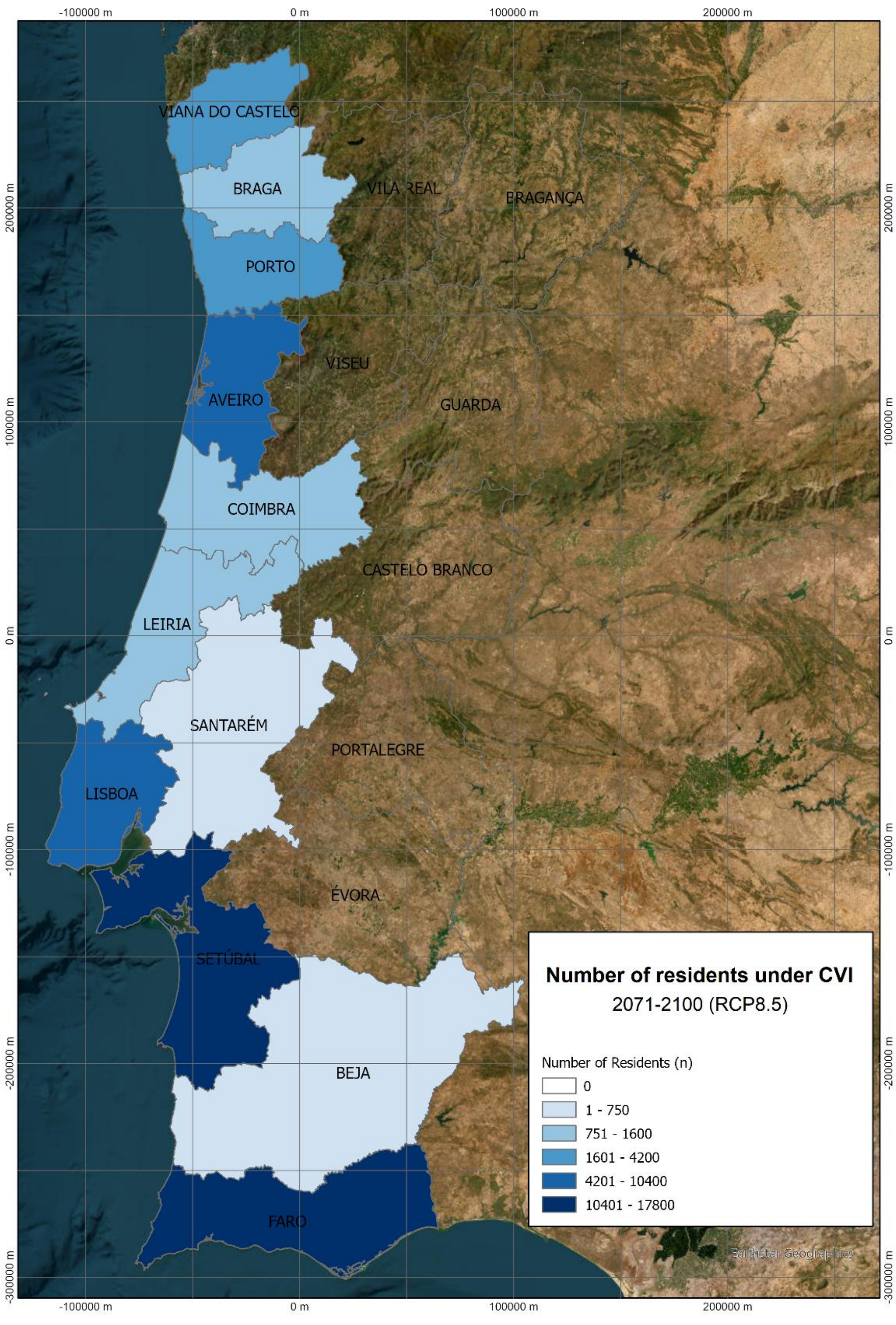


Figure 3.3.9 – Same as in Fig. 3.3.3, but by the end of the 2071-2100 period under the RCP8.5 scenario.

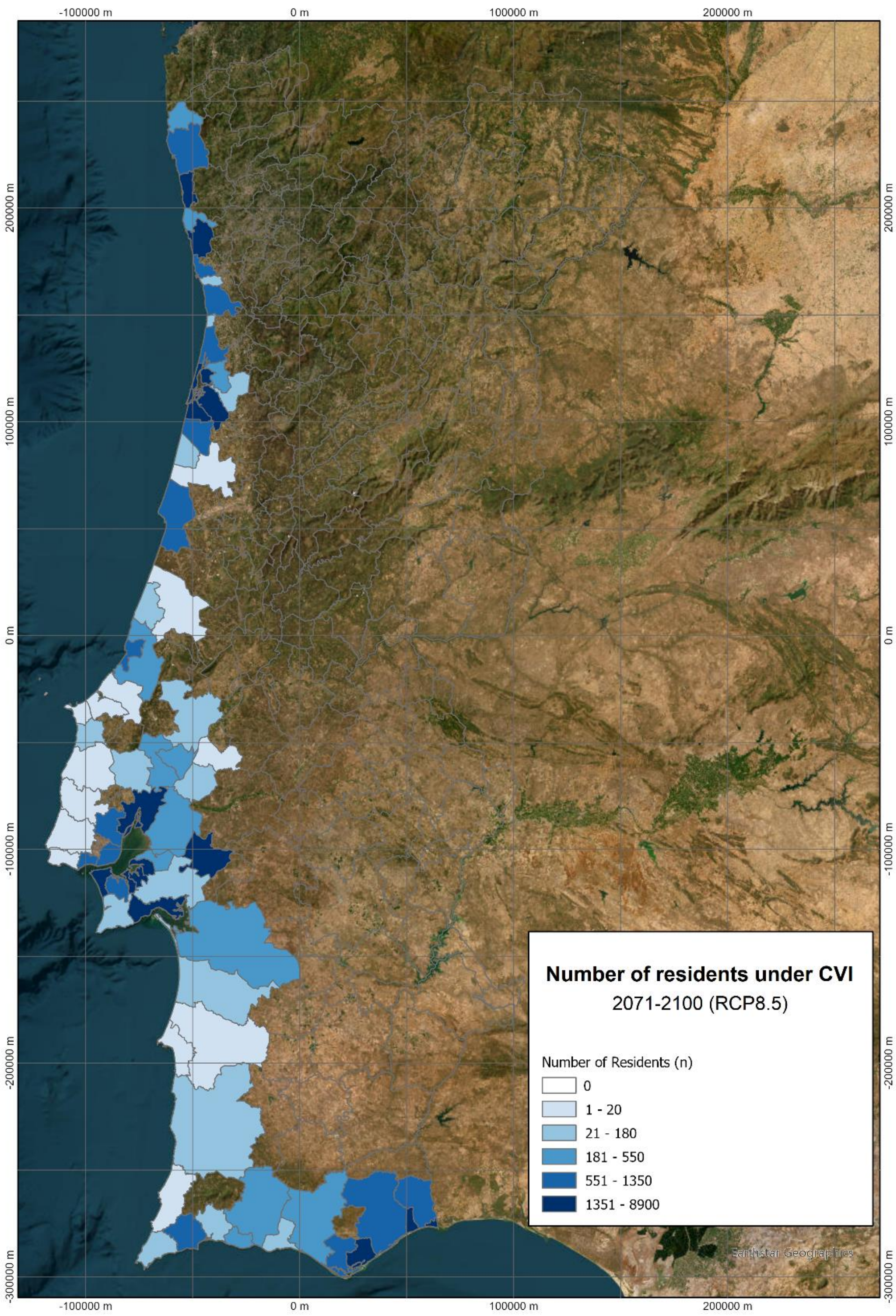


Figure 3.3.10 – Same as in Fig. 3.3.4, but by the end of the 2071-2100 period under the RCP8.5 scenario.

The total number of residents in areas projected to become under CVI, according to the CENSOS 2021, is 45330 and 45606 by 2070 under the RCP4.5 and RCP8.5 scenarios, respectively. By 2100, these numbers are projected to increase to 52772 and 60463, under RCP4.5 and RCP8.5, respectively. Between districts, most of the residents projected to become vulnerable are located in Faro, Setúbal and Aveiro (Figure 3.3.11). This is mostly due to populated low-lying areas such as near Ria Formosa and the Guadiana River estuary, the Tagus and Sado rivers estuaries, and the Ria de Aveiro.

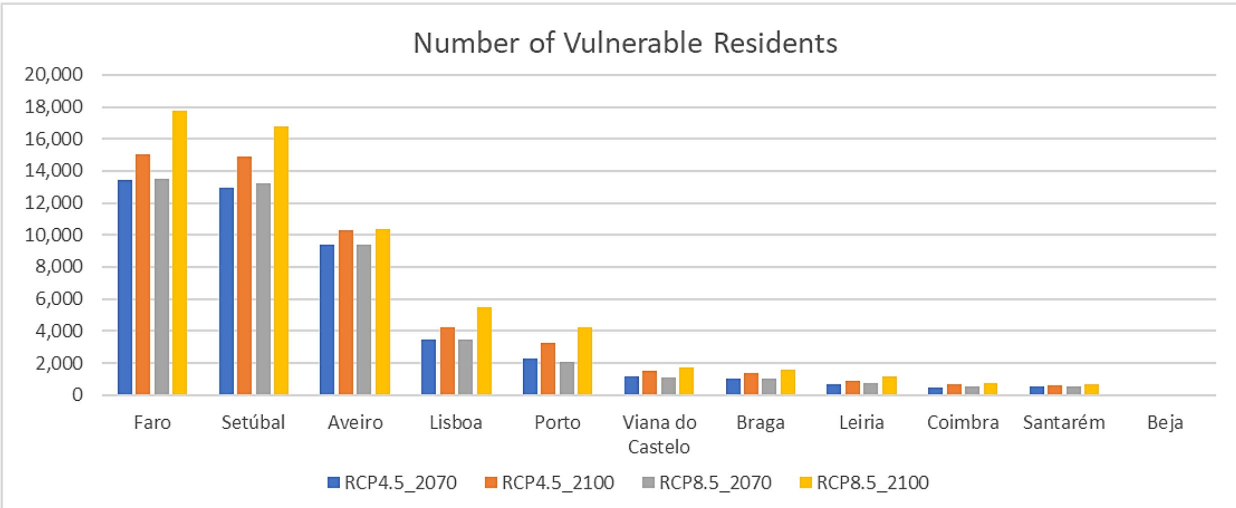


Figure 3.3.11 – Number of residents inhabiting areas projected to become under CVI, for each future period (represented by the end of the 2041-2070 and 2071-2100) and scenario (RCP4.5 and RCP8.5).

The demographic analysis (number of buildings projected to become under CVI in the future), according to the CENSOS 2021, by districts and municipalities, is shown in Figure 3.3.12 to Figure 3.3.19, respectively, considering all future periods and scenarios.

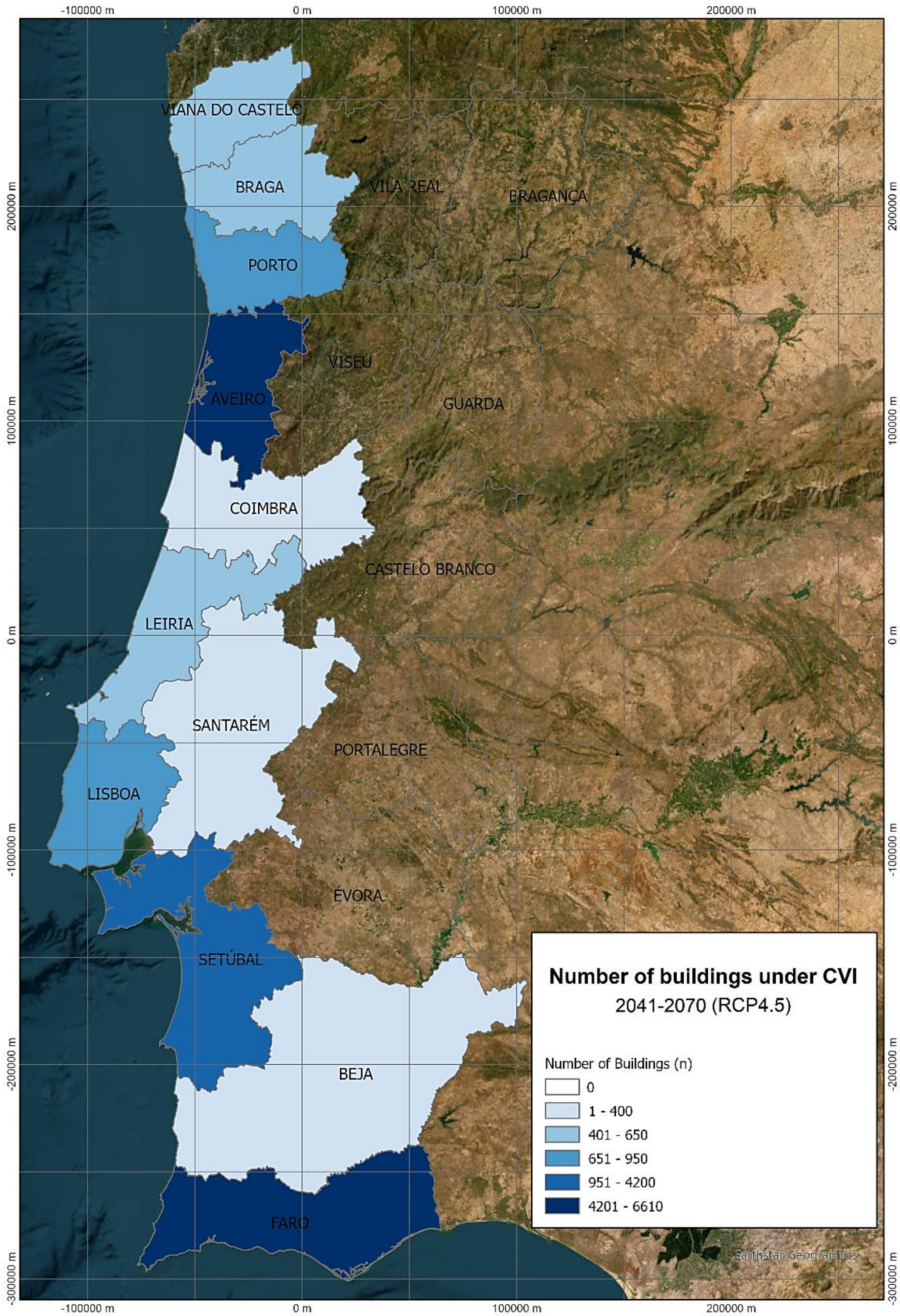


Figure 3.3.12 – Demographic analysis, expressed by the number of buildings projected to become under CVI in the future (by the end of the 2041-2070 period, under RCP4.5), according to the CENSOS 2021, by districts of Mainland Portugal. Note that the color scale intervals are not uniform, being divided by quantiles (0%, 1-20%, 21-40%, 41-60%, 61-80% and 81-100%) considering the national range of values.

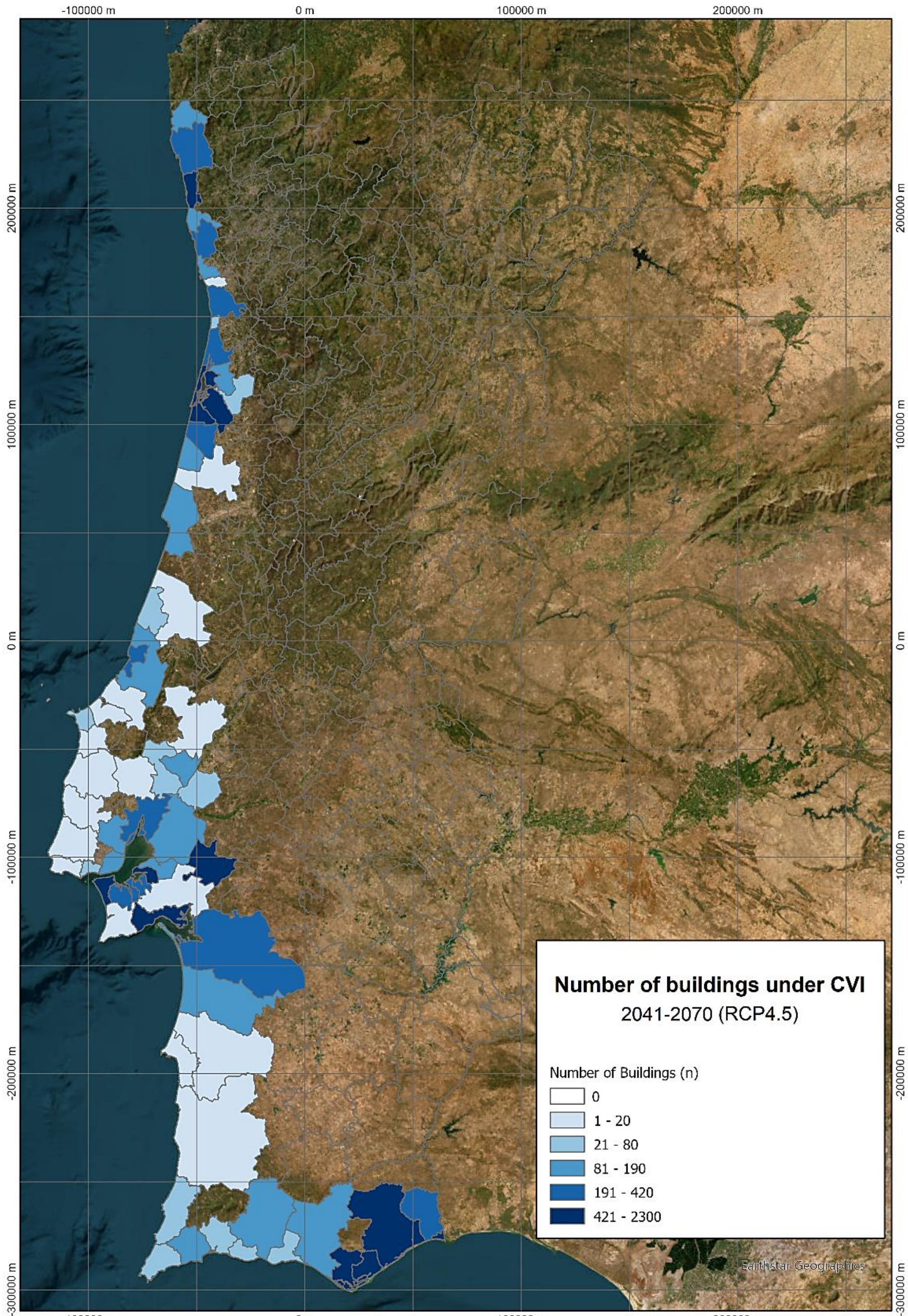


Figure 3.3.13 – Demographic analysis, expressed by the number of buildings projected to become under CVI in the future (by the end of the 2041-2070 period, under RCP4.5), according to the CENSOS 2021, by municipalities of Mainland Portugal. Note that the color scale intervals are not uniform, being divided by quantiles (0%, 1-20%, 21-40%, 41-60%, 61-80% and 81-100%) considering the national range of values.

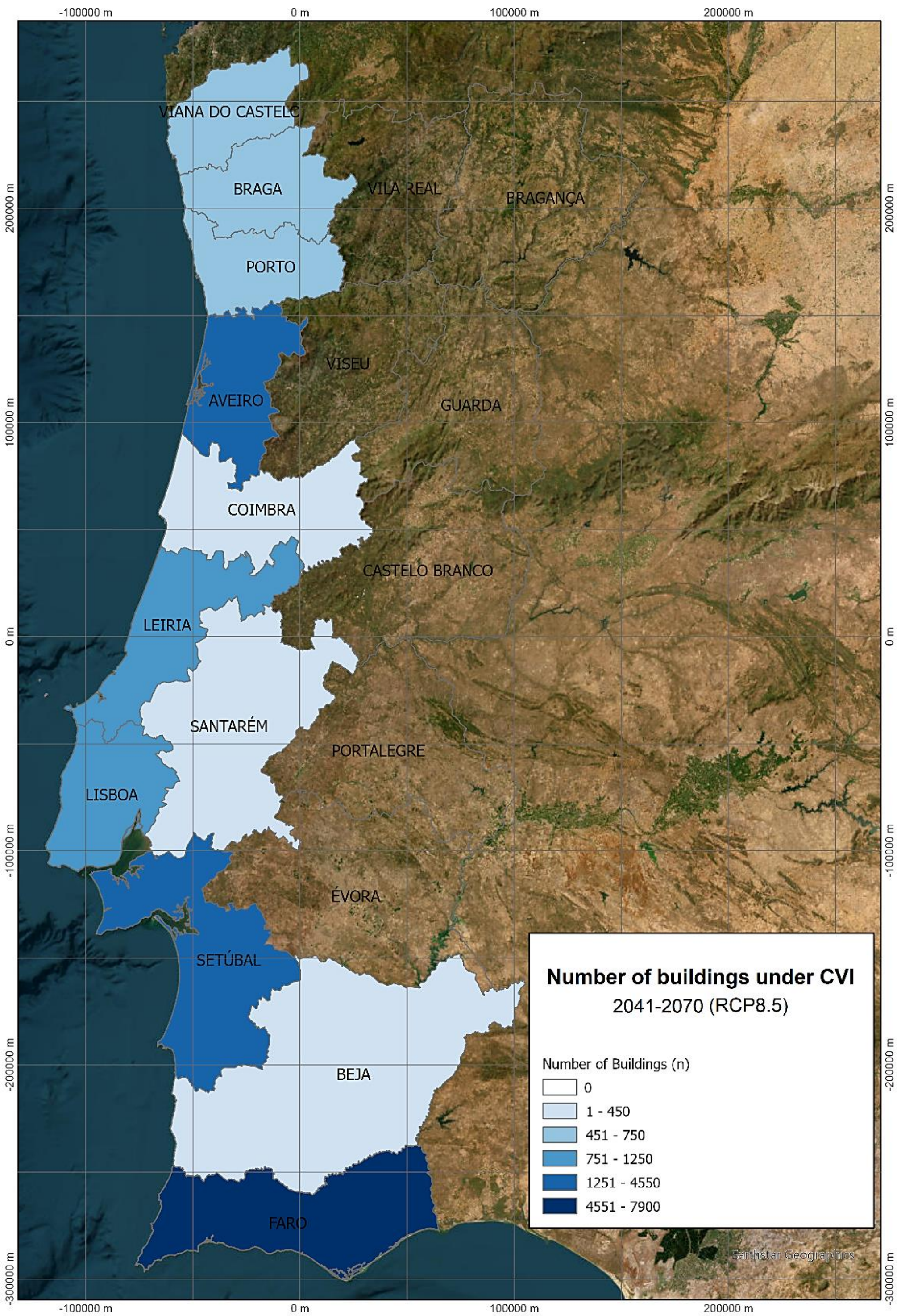


Figure 3.3.14 – Same as in Fig. 3.3.12, but for the RCP8.5 scenario.

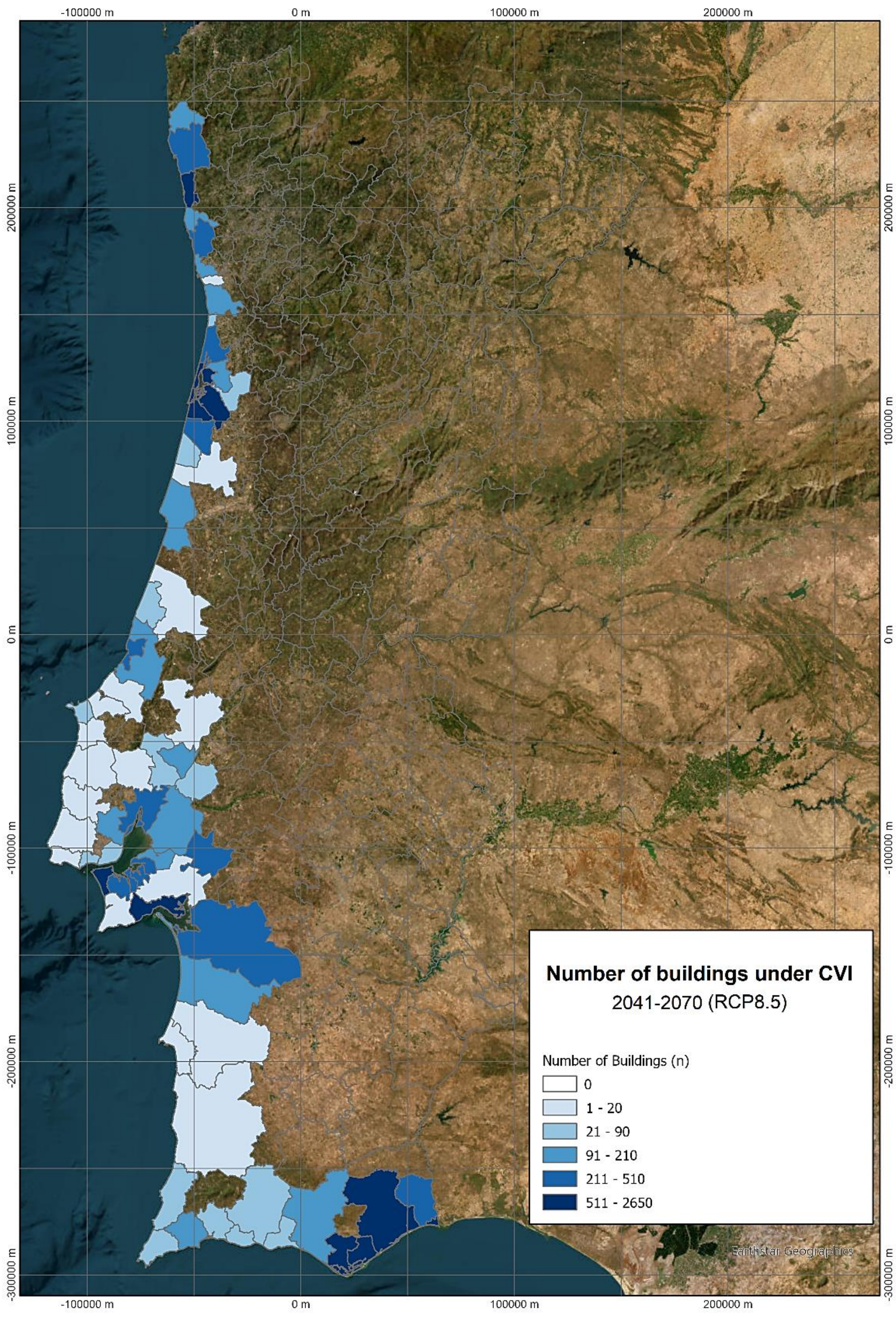


Figure 3.3.15 – Same as in Fig. 3.3.13, but for the RCP8.5 scenario.

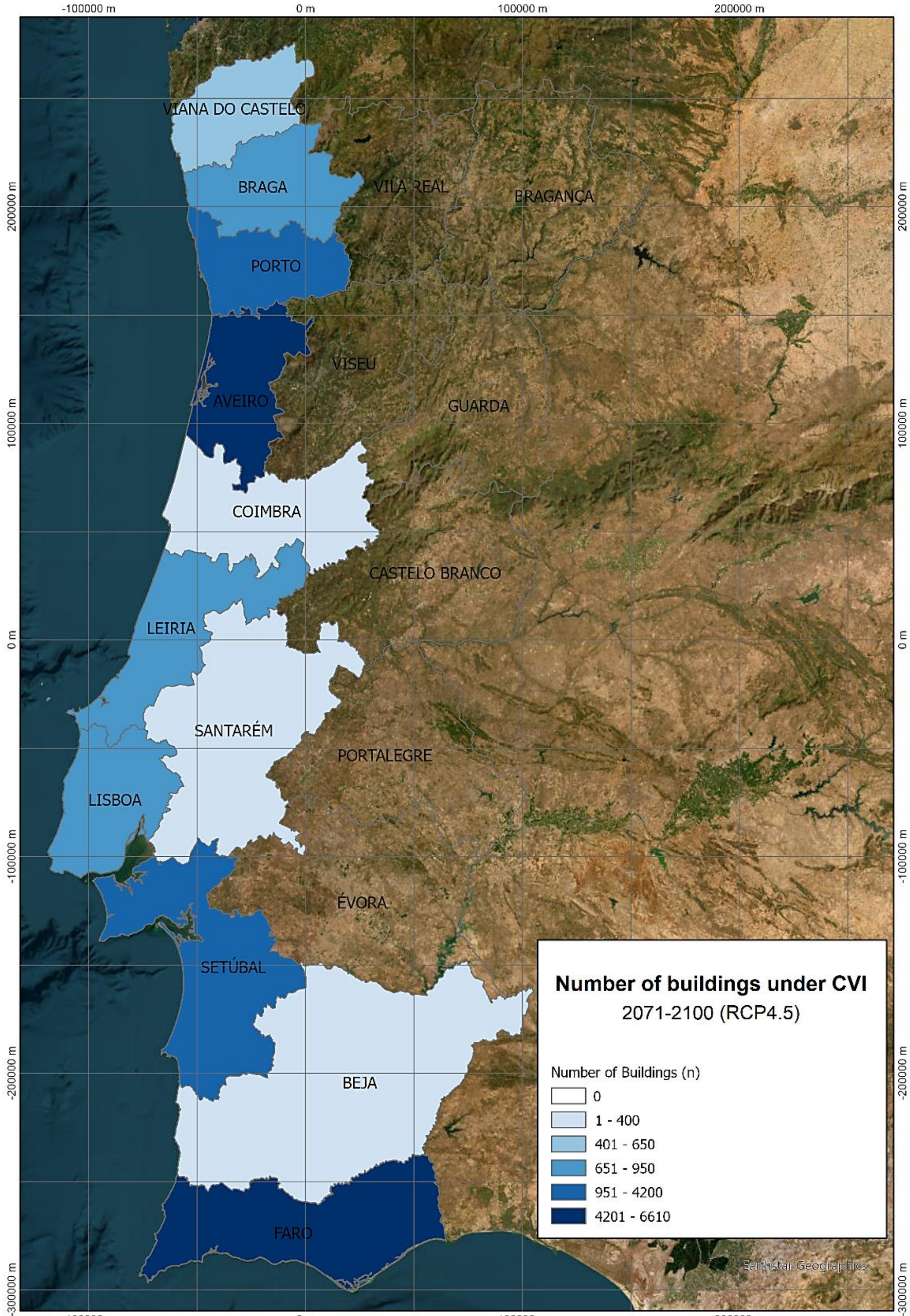


Figure 3.3.16 – Same as in Fig. 3.3.12, but by the end of the 2071-2100 period under the RCP4.5 scenario.

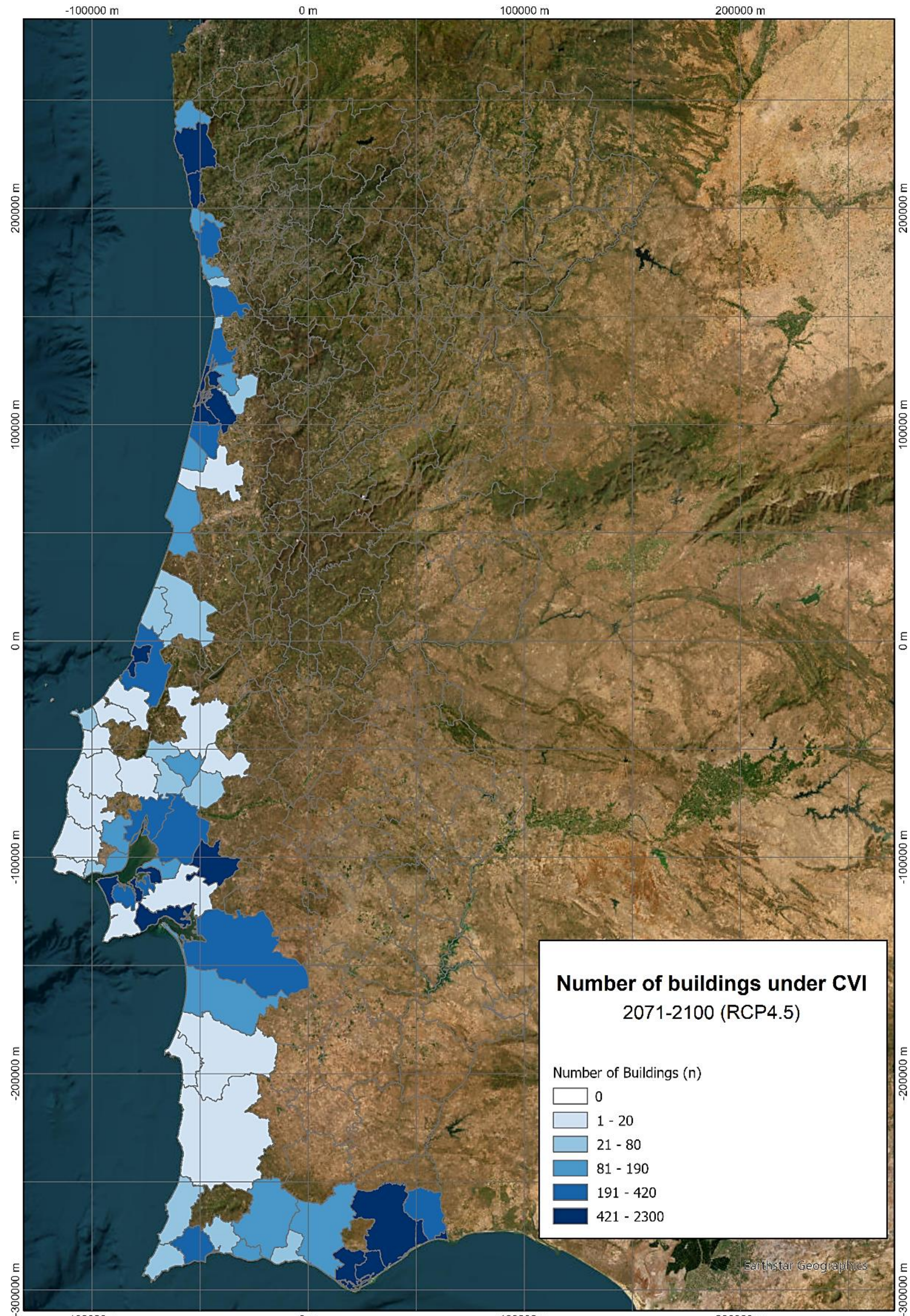


Figure 3.3.17 – Same as in Fig. 3.3.13, but by the end of the 2071-2100 period under the RCP4.5 scenario.

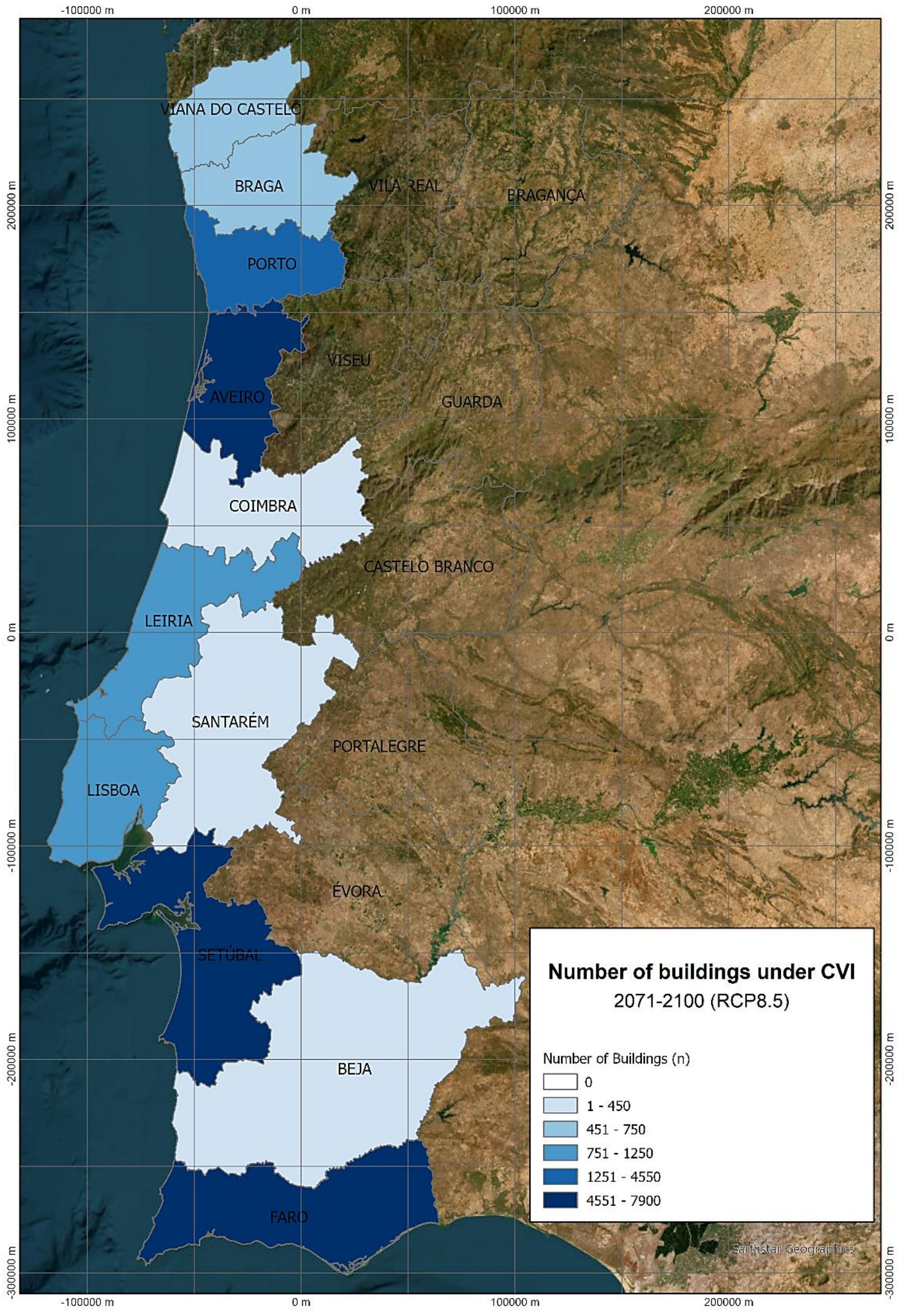


Figure 3.3.18 – Same as in Fig. 3.3.12, but by the end of the 2071-2100 period under the RCP8.5 scenario.

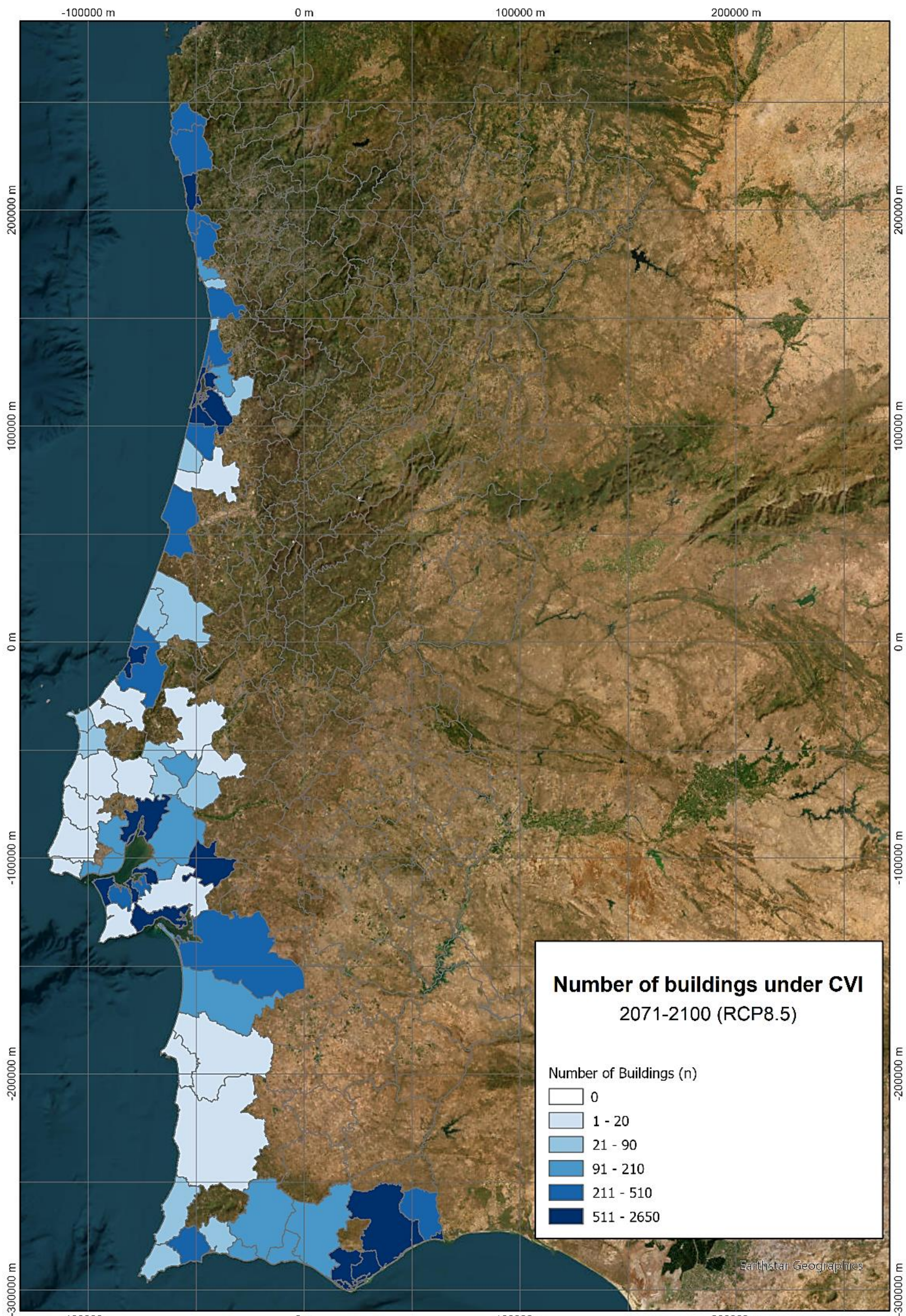


Figure 3.3.19 – Same as in Fig. 3.3.13, but by the end of the 2071-2100 period under the RCP8.5 scenario.

The total number of buildings within the Portuguese coastal areas projected to become vulnerable is set at 17584 and 17854, by 2070, under the RCP4.5 and RCP8.5, respectively. Towards the end of the 21st century

(2071-2100), these numbers are projected to increase towards 20288 and 23210, respectively. Such values are, nevertheless, based on the number of buildings existing in 2021, according to the CENSOS 2021. Between districts, most of the building projected to become vulnerable are located in Faro, Aveiro and Setúbal (Figure 3.3.20). This is mostly due to populated low-lying areas such as near Ria Formosa and the Guadiana River estuary, the Tagus and Sado rivers estuaries, and the Ria de Aveiro. In fact, the Vila Real de Santo António, Olhão and Tavira municipalities, within the Faro district, amount to 2292, 1510 and 1022 (2607, 1912 and 1141) vulnerable buildings under RCP4.5 (RCP8.5) by 2071-2100, totalizing 7857, 2598 and 1293 (8850, 3341 and 1461) residents, respectively. Similarly, within the Aveiro district, the Murtosa, Ovar and Aveiro municipalities amount to 1603, 1198 and 1024 (1629, 1227 and 1038) vulnerable buildings under RCP4.5 (RCP8.5) by 2071-2100, totalizing 3958, 2063 and 2447 (3965, 2094 and 2450) vulnerable residents, respectively. In Setúbal, the number of vulnerable buildings is especially high in the Almada municipality, totalizing 1071 and 1163 under the RCP4.5 and RCP8.5 scenarios (2071-2100), representing 4224 and 4809 vulnerable residents, respectively.

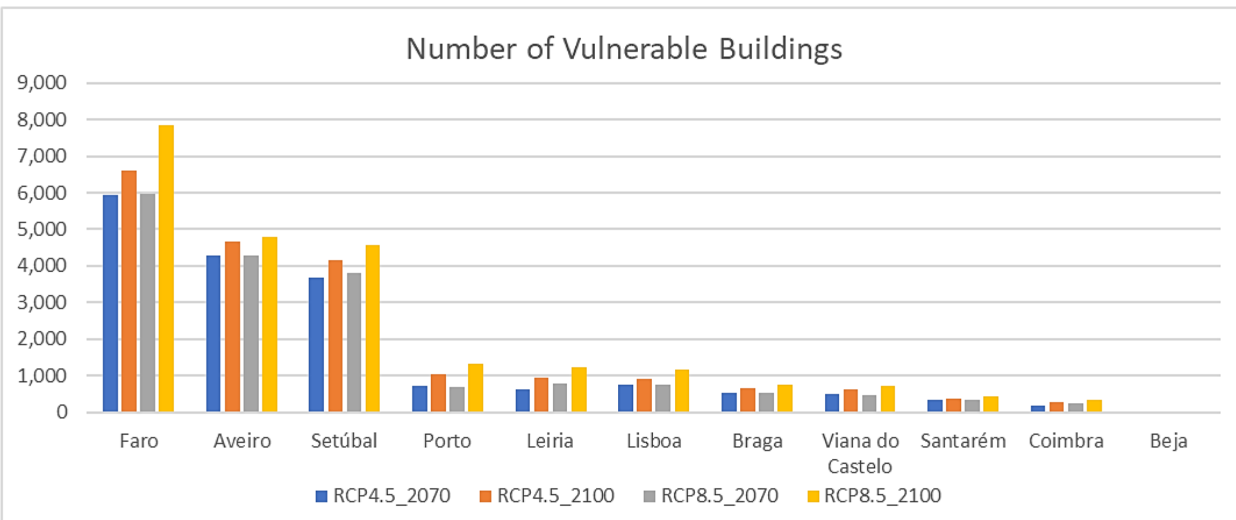


Figure 3.3.20 – Number of buildings in areas projected to become under CVI, for each future period (represented by the end of the 2041-2070 and 2071-2100) and scenario (RCP4.5 and RCP8.5).

A summary of the number of residents and buildings projected to become under CVI throughout the future projected periods and scenarios is provided in Table 3.3.1.

Table 3.3.1 – Number of buildings and residents in areas projected to become under CVI, for each future period (2041-2070 and 2071-2100) and scenario (RCP4.5 and RCP8.5).

Distrito	2041-2070 (RCP4.5)		2041-2070 (RCP8.5)		2071-2100 (RCP4.5)		2071-2100 (RCP8.5)	
	Buildings	Residents	Buildings	Residents	Buildings	Residents	Buildings	Residents
Viana do Castelo	487	1157	480	1121	625	1509	721	1698
Braga	527	1038	516	1024	662	1390	738	1588
Porto	732	2263	674	2053	1054	3281	1338	4196
Aveiro	4297	9359	4288	9381	4672	10285	4796	10394
Coimbra	191	495	238	564	266	640	335	756
Leiria	640	641	781	750	949	909	1240	1163
Santarém	334	529	338	519	382	584	448	677
Lisboa	746	3461	751	3494	901	4264	1159	5476
Setúbal	3691	12950	3801	13205	4161	14886	4578	16769
Beja	10	14	11	15	13	15	19	21
Faro	5929	13423	5976	13480	6603	15009	7838	17725
All coastal districts	17584	45330	17854	45606	20288	52772	23210	60463

The TICs are shown, by districts and municipalities, in Figure 3.3.21 to Figure 3.3.28, considering the RCP8.5 scenario, by 2100. These accountable costs only consider the real estate property at the present market value, of buildings and land, with additional loss of taxation and municipality costs of urbanization.

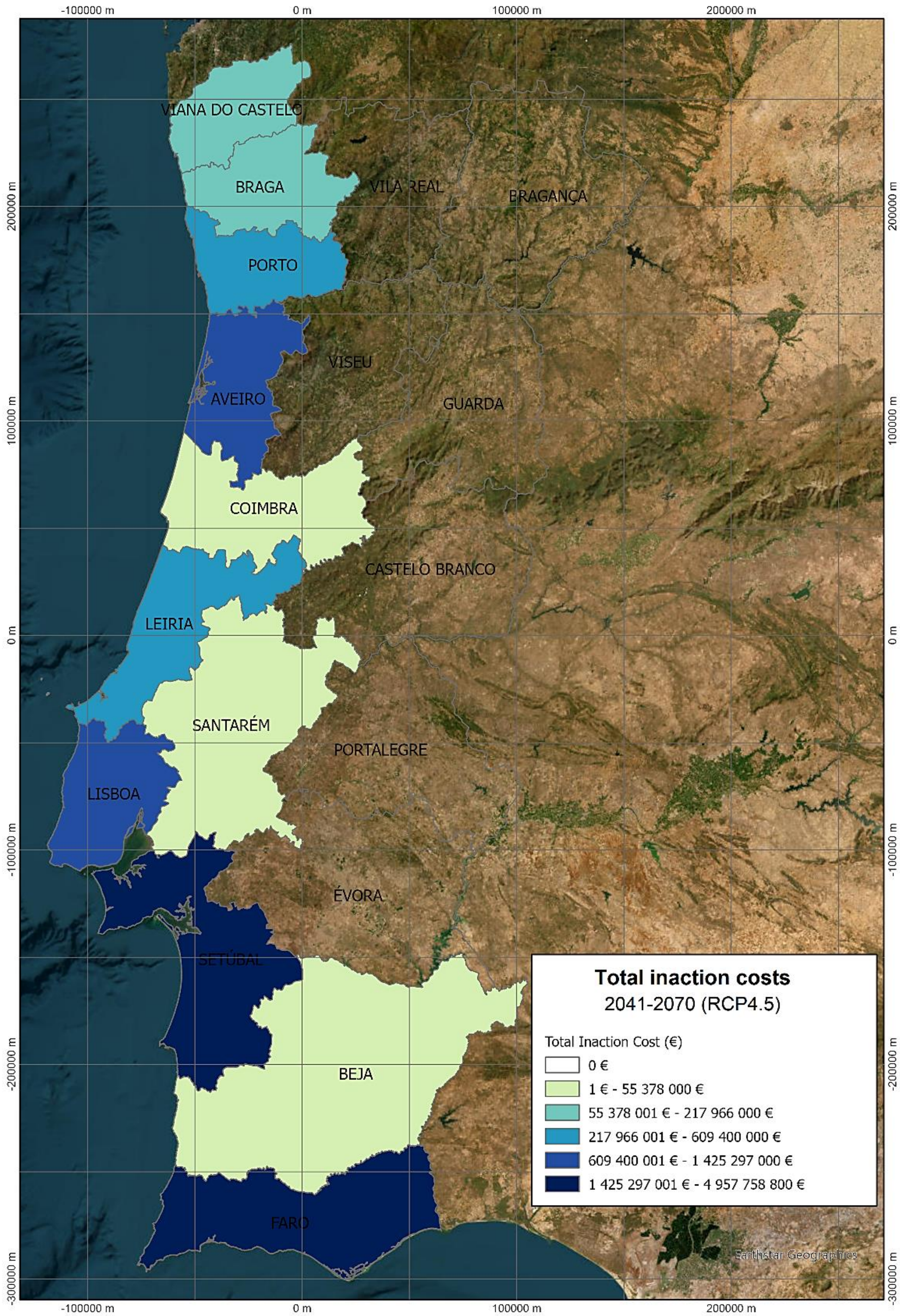


Figure 3.3.21 – TIC along the areas projected to become under CVI in the future (by the end of the 2041-2070 period, under RCP4.5), by districts of Mainland Portugal. Note that the color scale intervals are not uniform, being divided by quantiles (0%, 1-20%, 21-40%, 41-60%, 61-80% and 81-100%) considering the national range of values.

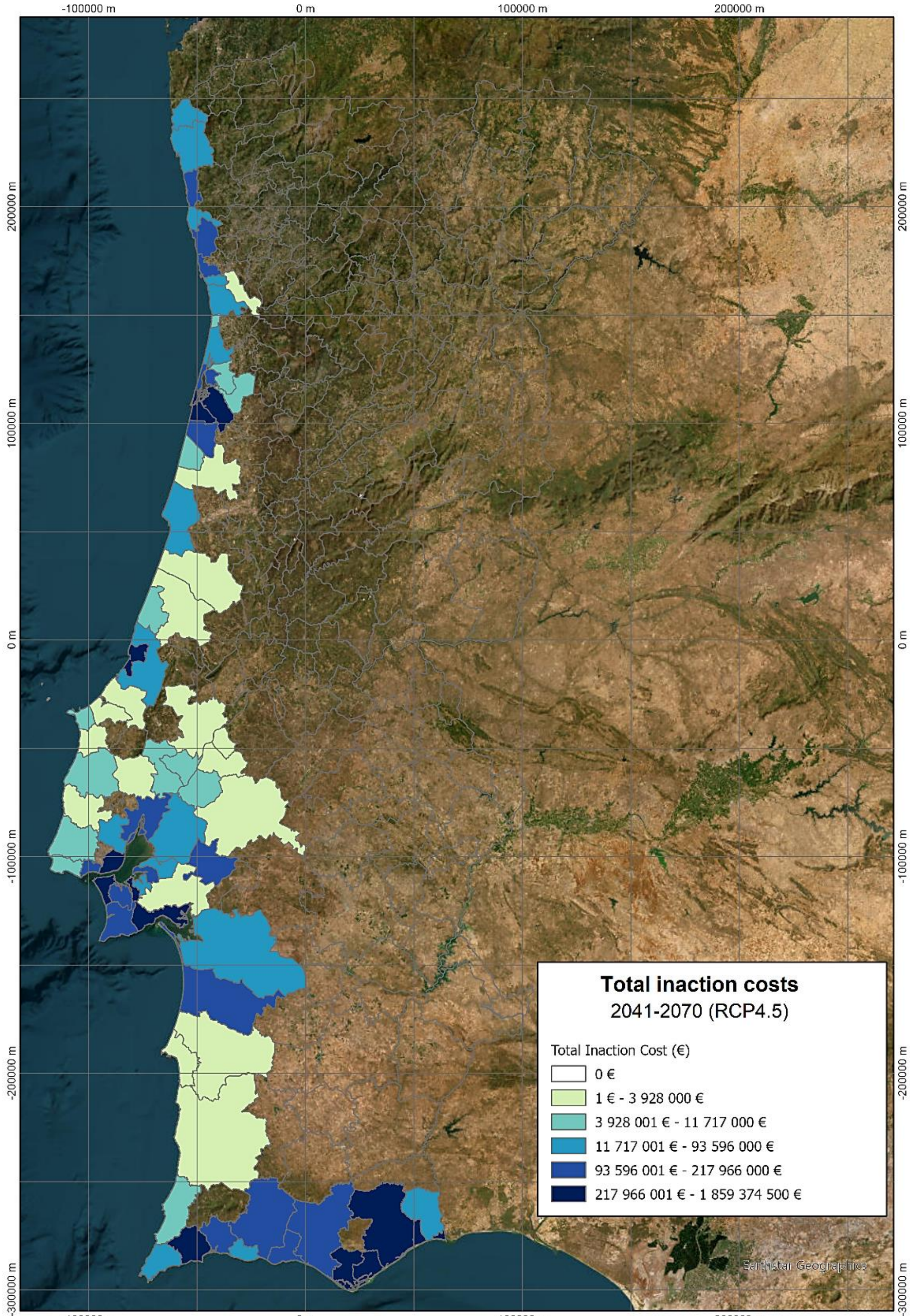


Figure 3.3.22 – TIC along the areas projected to become under CVI in the future (by the end of the 2041-2070 period, under RCP4.5), by municipalities of Mainland Portugal. Note that the color scale intervals are not uniform, being divided by quantiles (0%, 1-20%, 21-40%, 41-60%, 61-80% and 81-100%) considering the national range of values.

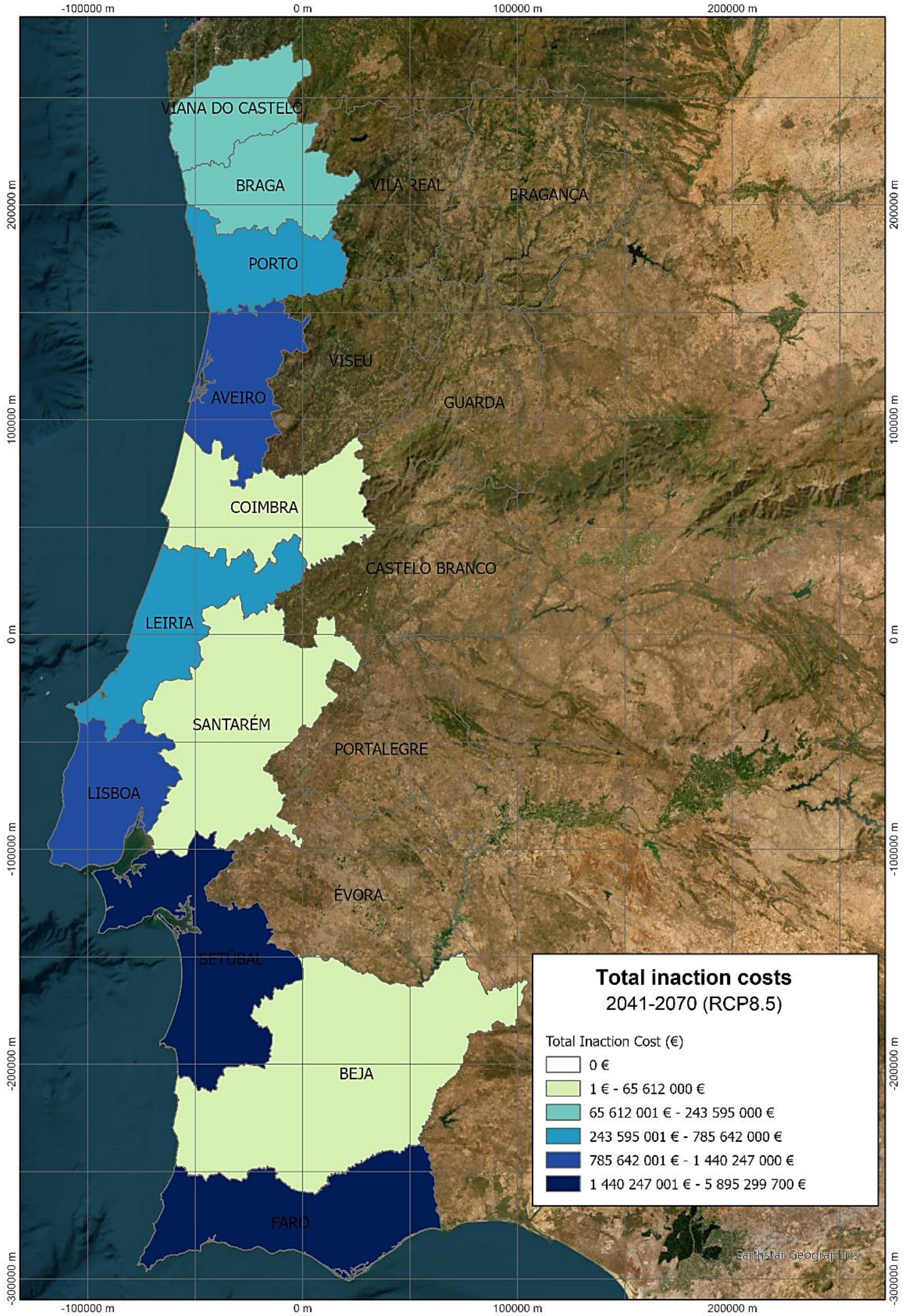


Figure 3.3.23 – Same as in Fig. 3.3.21, but for the RCP8.5 scenario.

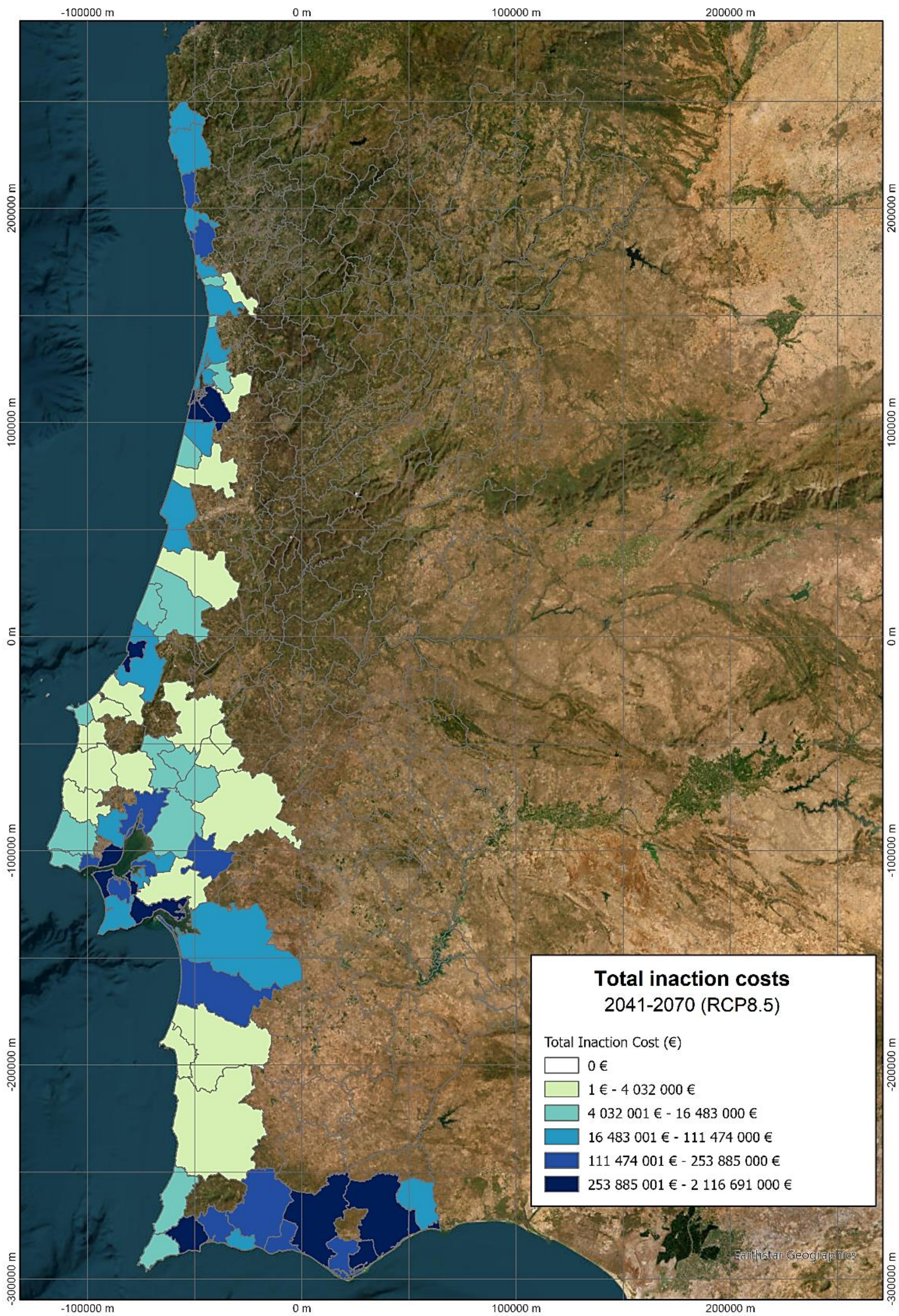


Figure 3.3.24 – Same as in Fig. 3.3.22, but for the RCP8.5 scenario.

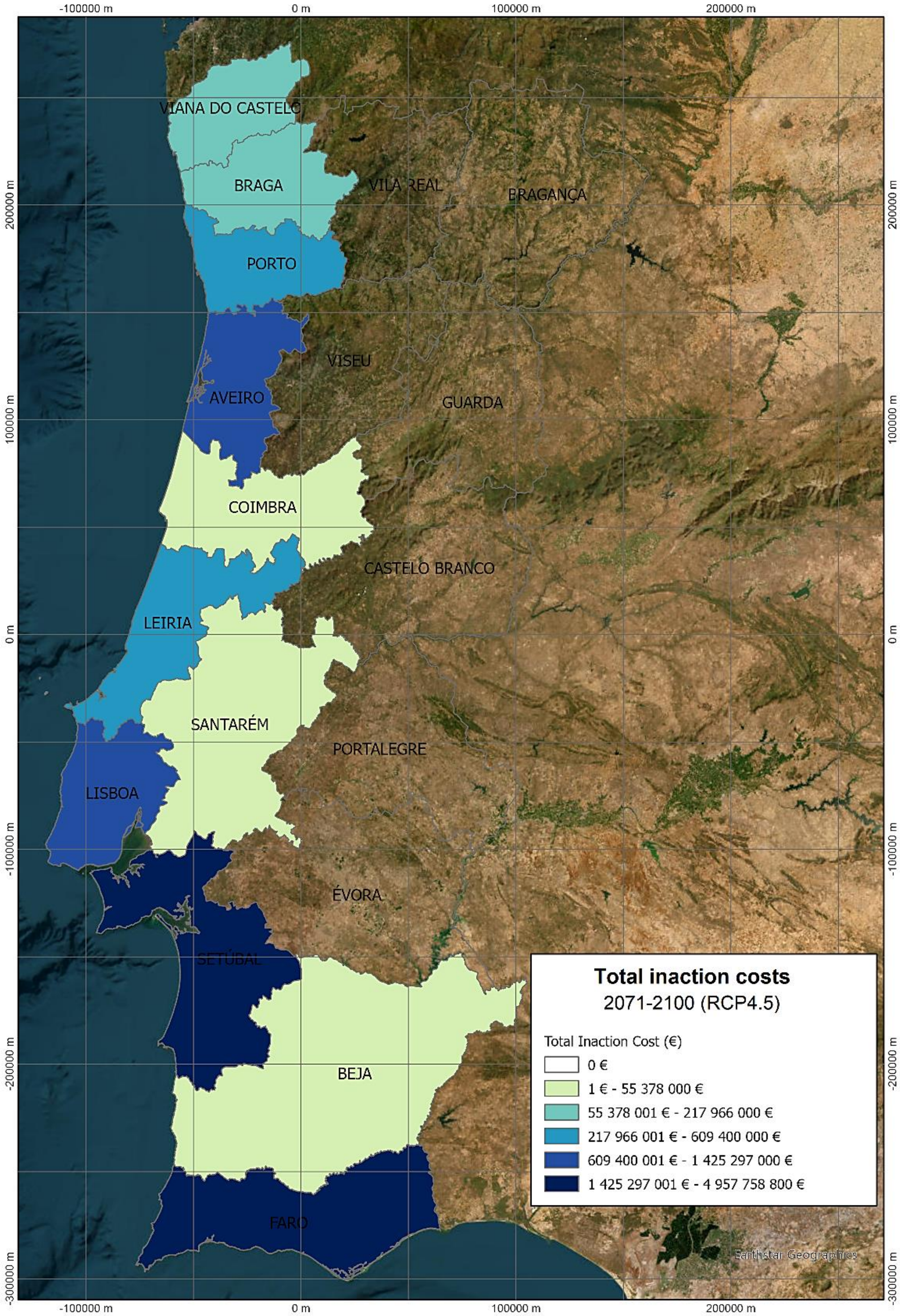


Figure 3.3.25 – Same as in Fig. 3.3.21, but by the end of the 2071-2100 period under the RCP4.5 scenario.

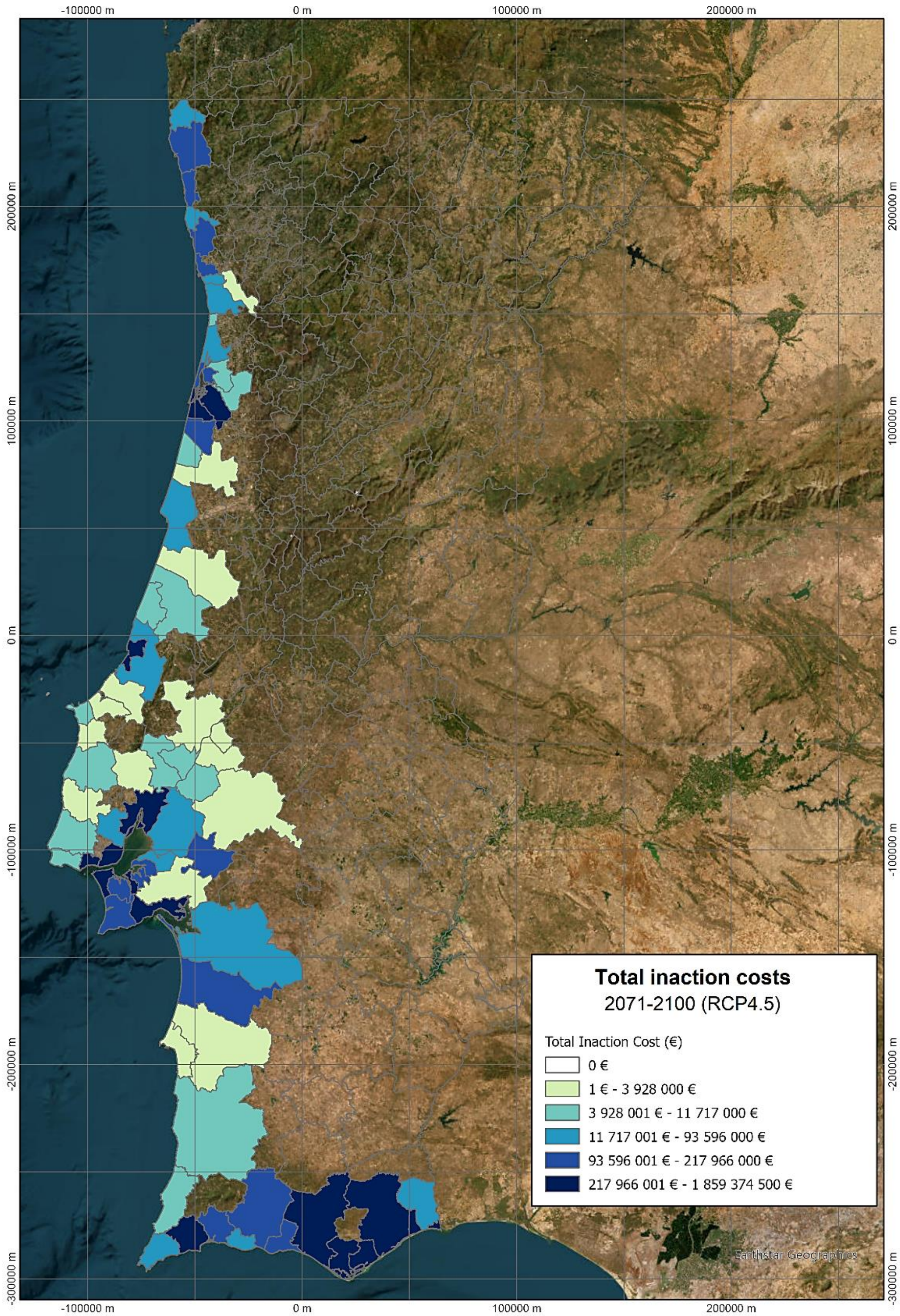


Figure 3.3.26 – Same as in Fig. 3.3.22, but by the end of the 2071-2100 period under the RCP4.5 scenario.

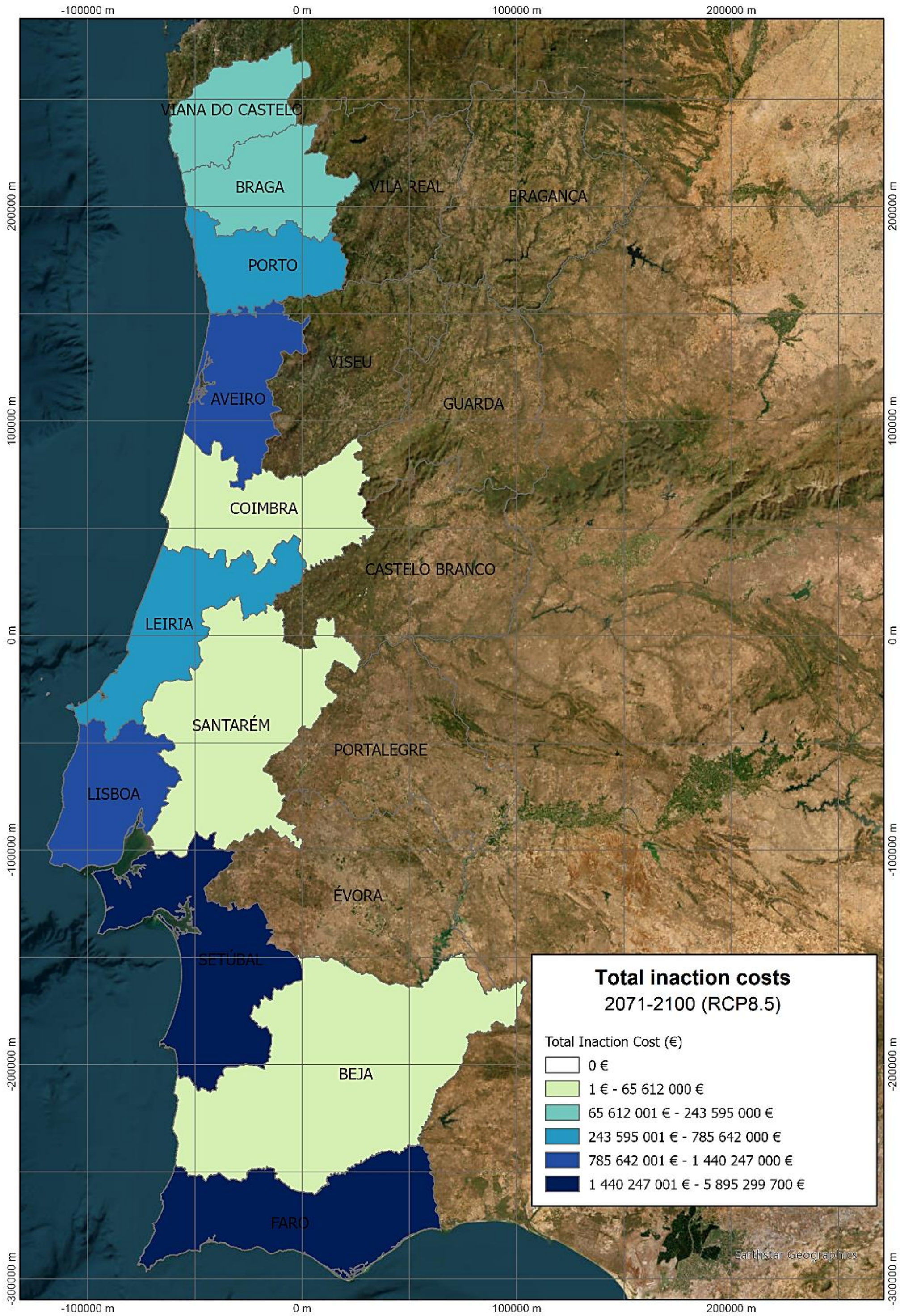


Figure 3.3.27 – Same as in Fig. 3.3.21, but by the end of the 2071-2100 period under the RCP8.5 scenario.

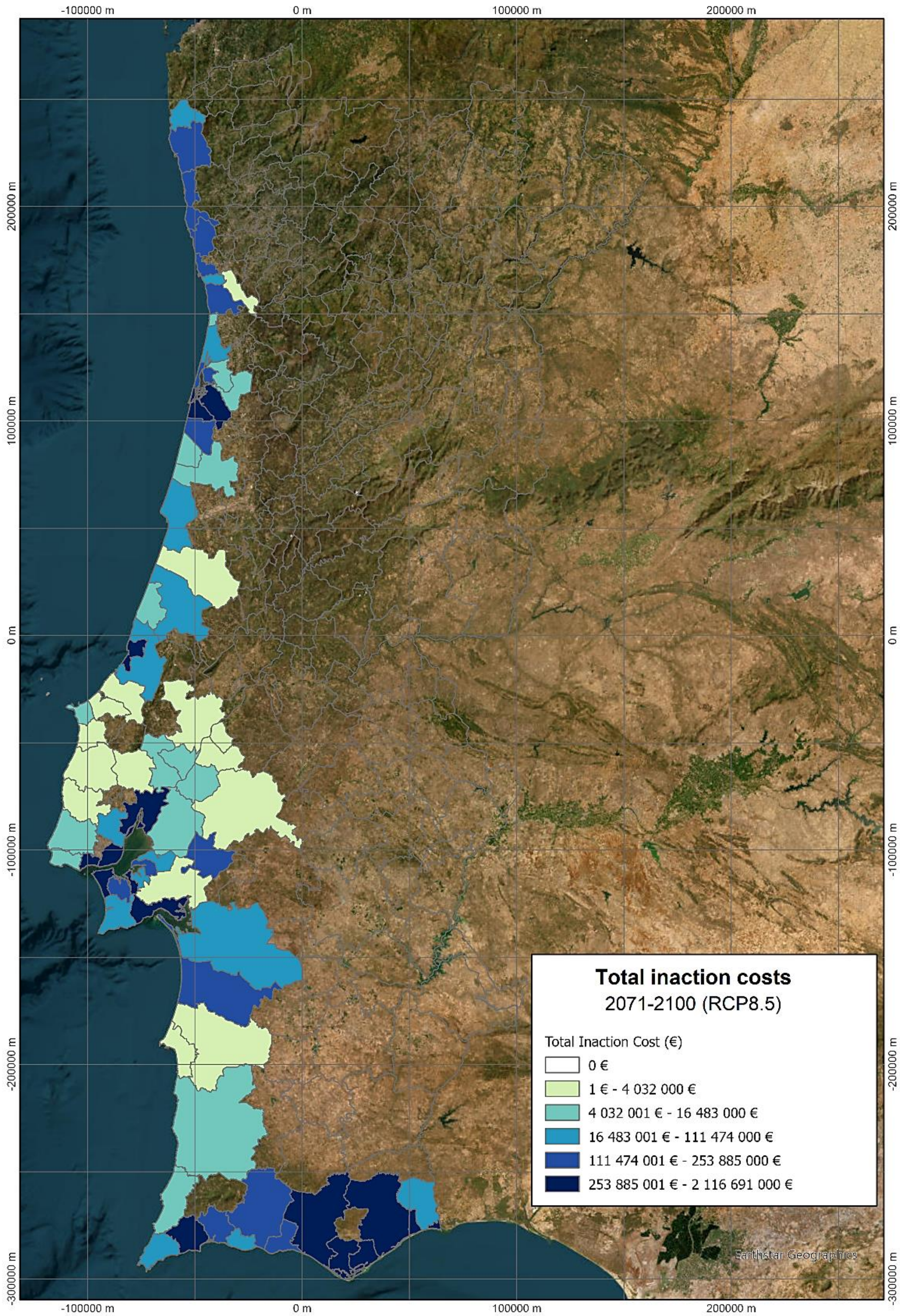


Figure 3.3.28 – Same as in Fig. 3.3.22, but by the end of the 2071-2100 period under the RCP8.5 scenario.

Other indirect costs related to critical coastal infrastructures, such as ports, harbours, marines, fishing and nautical ports, airports, and military infrastructures, due to the continuous increases in the sea level, are not considered, due to the challenges involving its countability. The TICs, by each vulnerable district of Mainland Portugal, are shown in Figure 3.3.29 to Figure 3.3.32, considering all future periods and scenarios, from the low-end (2041-2070 under RCP4.5) to the upper-end (2071-2100 under RCP8.5) TICs. Within each instance, the TICs are given by a range of values, from the minimum TIC ($TICmin$) to the maximum TIC ($TICmax$). The juxtaposition between all periods and scenarios also promotes a range of TICs for the future vulnerable areas, considering inter-period and inter-scenario uncertainties (lower TIC projections until the end of the 2041-2070 period under a moderate scenario and higher TIC projections towards the end of the 2071-2100 period under a high-emissions scenario).

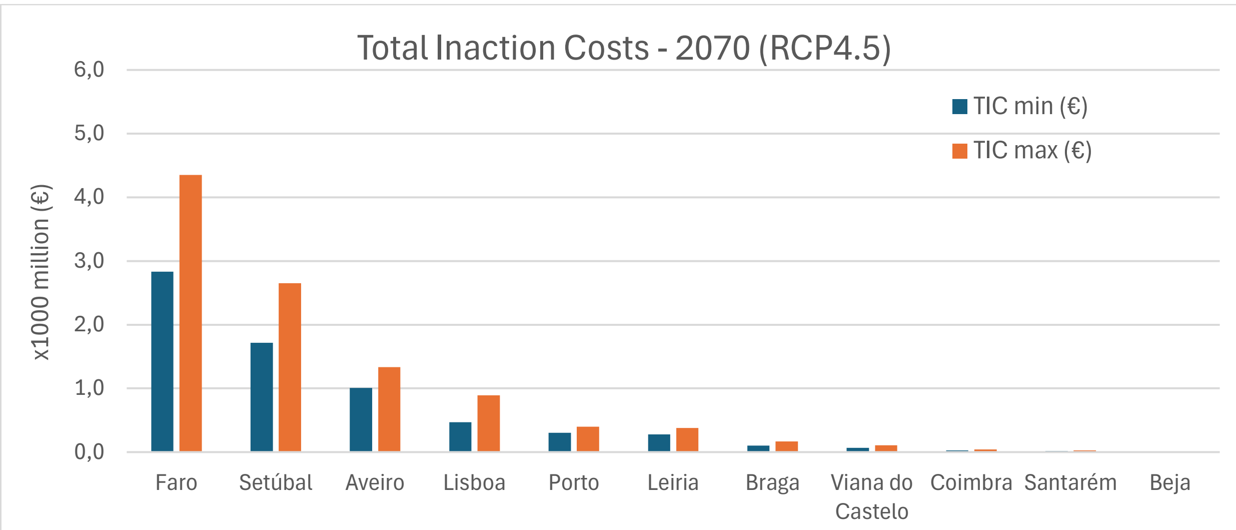


Figure 3.3.29 – Minimum and maximum projected TICs, considering areas projected to become under CVI across each district of Mainland Portugal, by the end of the 2041-2070 future period, under the RCP4.5 scenario.

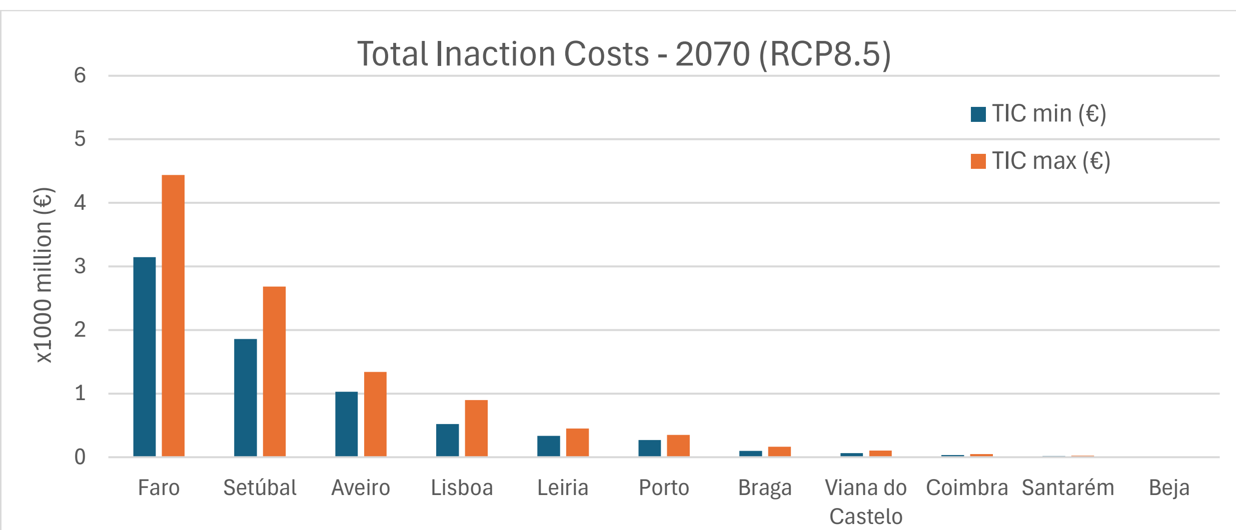


Figure 3.3.30 – Same as in Fig. 3.3.29, but for the RCP8.5 scenario.

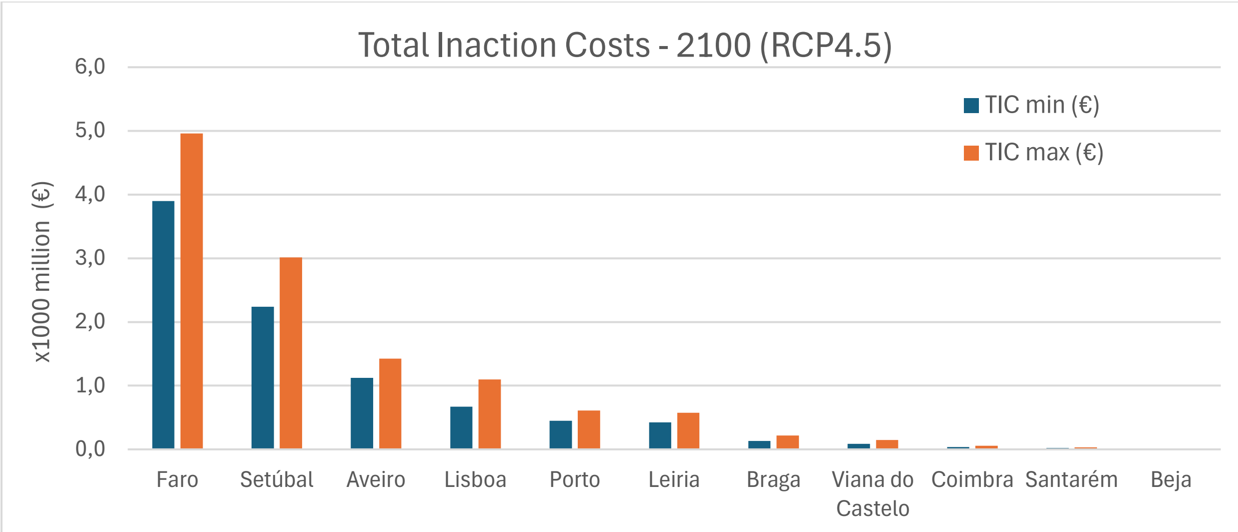


Figure 3.3.31 – Same as in Fig. 3.3.29, but by the end of the 2071-2100 future period.

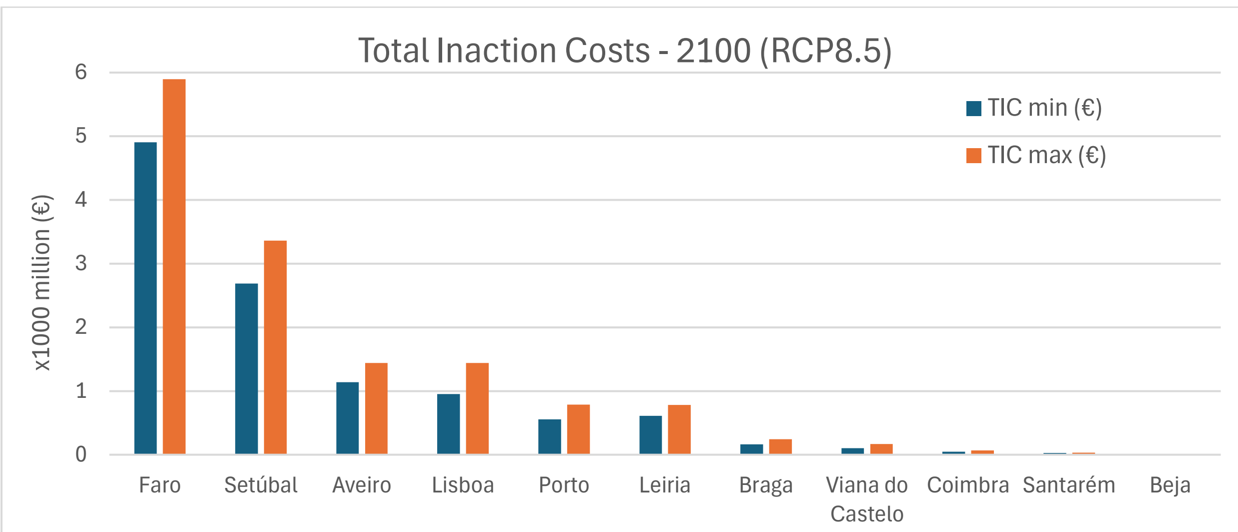


Figure 3.3.32 – Same as in Fig. 3.3.29, but by the end of the 2071-2100 future period under the RCP8.5 scenario.

Considering the entire future projected areas under CVI across Mainland Portugal, the expected TICs vary between 6822 and 10354 million € by the end of the 2041-2070 time-slice under RCP4.5, and between 11200 and 14223 million € by the end of the 2071-2100 under RCP8.5. Note that these values are representative of the year 2023. Similarly to the number of residents and buildings projected as under CVI in the future, Faro district remains the one projected to be most affected in terms of TICs. These are expected to range between 2831 and 4349 million € (2070 under RCP4.5), and 4908 and 5895 million € (2100 under RCP8.5), *i.e.*, more than one third of the TICs estimated for the entire Portuguese coastlines. In the opposite end of the list, Beja district is found, with TICs projected to range between 3.153 and 3.590 million € (2070 under RCP4.5), and 3.617 and 4.206 million € (2100 under RCP4.5), *i.e.*, more than 3 orders of magnitude less (one thousandth) than for Faro. Note that throughout the Portuguese coastlines, there are only two municipalities showing projected maximum TICs above 1000 million € until the end of the 21st century (under RCP8.5), namely Vila Real de Santo António (2117 million €) and Almada (1669 million €). For the same period and scenario, there are six municipalities showing projected maximum TICs between 500 million € and 1000 million €, namely Tavira (906 million €), Lagos (762 million €), Ílhavo (708 million €), Lisboa (682 million €), Nazaré (663 million €) and Olhão (635 million €). The full projected TICs, per district, are displayed in Table 3.3.2 to Table 3.3.5.

Table 3.3.2 – Minimum and maximum future projected TICs, considering areas projected to become under CVI across each district of Mainland Portugal, by the end of the 2041-2070 future period, under the RCP4.5 scenario. Districts are organized from the highest to the lowest projected TICs.

Future projected TICs by 2070 under the RCP4.5 scenario		
District	TIC min (M€)	TIC max (M€)
Viana do Castelo	65.03	108.1
Braga	100.1	170.0
Porto	302.8	400.3
Aveiro	1007	1335
Coimbra	29.24	41.05
Leiria	278.0	377.5
Santarém	18.84	25.86
Lisboa	470.2	891.5
Setúbal	1717	2652
Beja	3.153	3.590
Faro	2831	4349
All coastal districts	6822	10354

Table 3.3.3 – Same as in Table 3.3.2, but under the RCP8.5 scenario.

Future projected TICs by 2070 under the RCP8.5 scenario		
District	TIC min (M€)	TIC max (M€)
Viana do Castelo	63.89	104.5
Braga	98.73	166.1
Porto	269.9	348.9
Aveiro	1031	1340
Coimbra	34.34	48.09
Leiria	334.2	452.4
Santarém	19.44	25.36
Lisboa	521.3	899.5
Setúbal	1861	2684
Beja	3.225	3.716
Faro	3145	4438
All coastal districts	7381	10511

Table 3.3.4 – Same as in Table 3.3.2, but by the end of the 2071-2100 future period.

Future projected TICs by 2100 under the RCP4.5 scenario		
District	TIC min (M€)	TIC max (M€)
Viana do Castelo	86.42	149.5
Braga	134.5	218.0
Porto	448.1	609.4
Aveiro	1124	1425
Coimbra	38.92	55.38
Leiria	422.8	572.2
Santarém	22.84	29.21
Lisboa	672.1	1099
Setúbal	2238	3016
Beja	3.617	4.205
Faro	3897	4957
All coastal districts	9089	12136

Table 3.3.5 – Same as in Table 3.3.2, but by the end of the 2071-2100 future period, under the RCP8.5 scenario.

Future projected TICs by 2100 under the RCP8.5 scenario		
District	TIC min (M€)	TIC max (M€)
Viana do Castelo	103.5	170.0
Braga	162.0	243.6
Porto	557.9	785.6
Aveiro	1138	1440
Coimbra	49.21	65.61
Leiria	612.6	783.4
Santarém	25.74	32.28
Lisboa	950.8	1439
Setúbal	2689	3363
Beja	3.688	4.059
Faro	4908	5895
All coastal districts	11200	14223

Finally, considering a slightly different approach, focusing simply on the total number of buildings projected as under CVI, by 2100 under the RCP8.5 scenario, the loss of 23210 buildings with an average of 4 apartments each with a living area of 112.4 m^2 (CENSOS 2021), for a medium cost of 1541€/m^2, a projected TIC of 16081 million € is obtained for Mainland Portugal. This value, although slightly higher than the previous TIC, is aligned with the more comprehensive approach.

3.3.1.4. Coastal Risk

The Coastal Risk Index (CRI) is given by a weighted combination of the CVI and the Exposure Vulnerability Index (EVI), such as $CRI = \sqrt{CVI * EVI}$. The CRI is therefore dependent on the EVI, quantified by the number of residents projected to be affected by episodic or permanent coastal flooding, in areas under CVI. The EVI combines the demographic analysis (DEM) and the TICs through a geometrical average, overweighting the latter (TICs), such as $EVI = \frac{1}{3}DEM * \frac{2}{3}\,TIC$. Note that the TICs themselves are already representative of the vulnerable population, and therefore provide a better metric of social vulnerability. Nevertheless, the TICs do not always represent social vulnerability in the same way, since, for example, in highly touristic areas (*e.g.*, Algarve, Troia), high TICs do not reflect well the social vulnerability of the residents. As both the number of residents and the TICs are normalized into three levels, the CRI is given by three levels as well (low, moderate and high). Figure 3.3.33 to Figure 3.3.36 depict the CRI along the four most critical regions of the Portuguese coastlines, considering the future projected TICs in Table 3.3.2 to Table 3.3.5, for the districts of Faro, Setúbal, Aveiro and Lisbon.

In the Ria Formosa region (Figure 3.3.33 to Figure 3.3.36), the CRI generally assumes moderate to high values, especially towards 2100. The coastal risk is especially high along densely populated coastal stretches (*e.g.*, Quarteira, Olhão, Armona, Fuseta, Tavira) or in areas with high economic value (*e.g.*, Faro International Airport, Quinta do Lago).

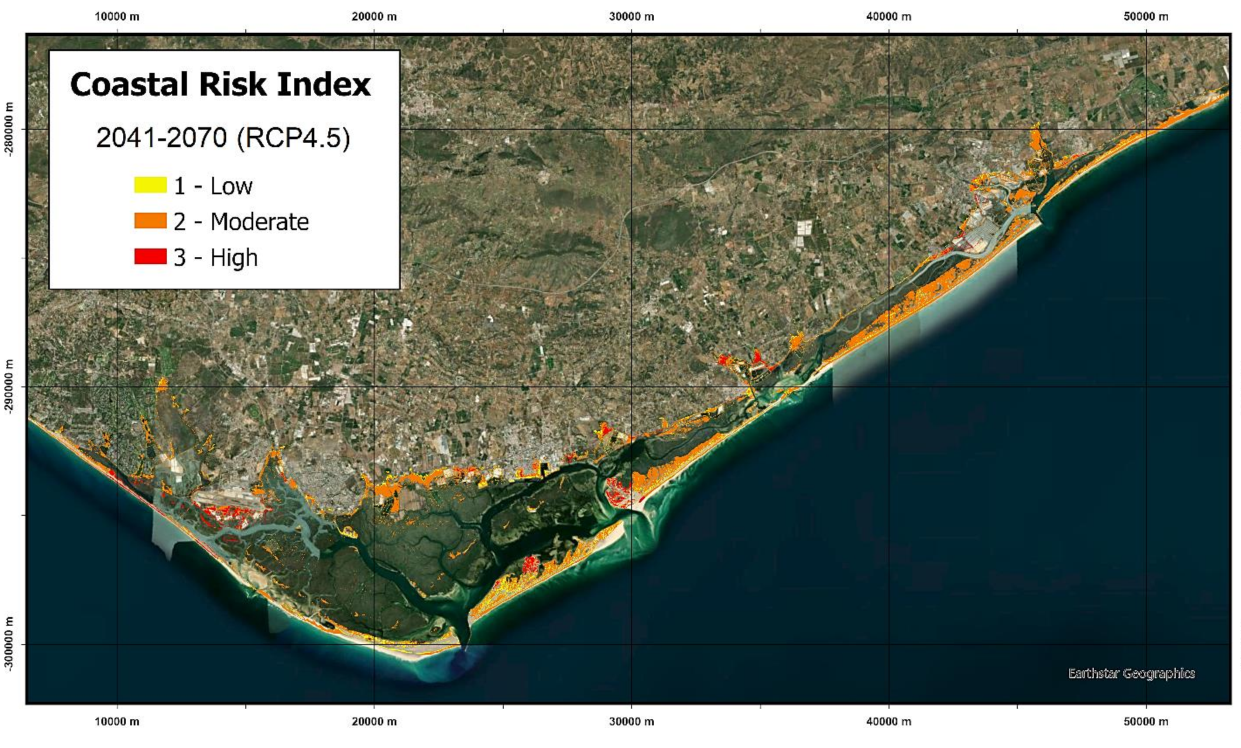


Figure 3.3.33 – Coastal Risk Index (CRI) for the Ria Formosa (Faro) region, by the end of the 2041-2070 future period, under the RCP4.5 scenario.

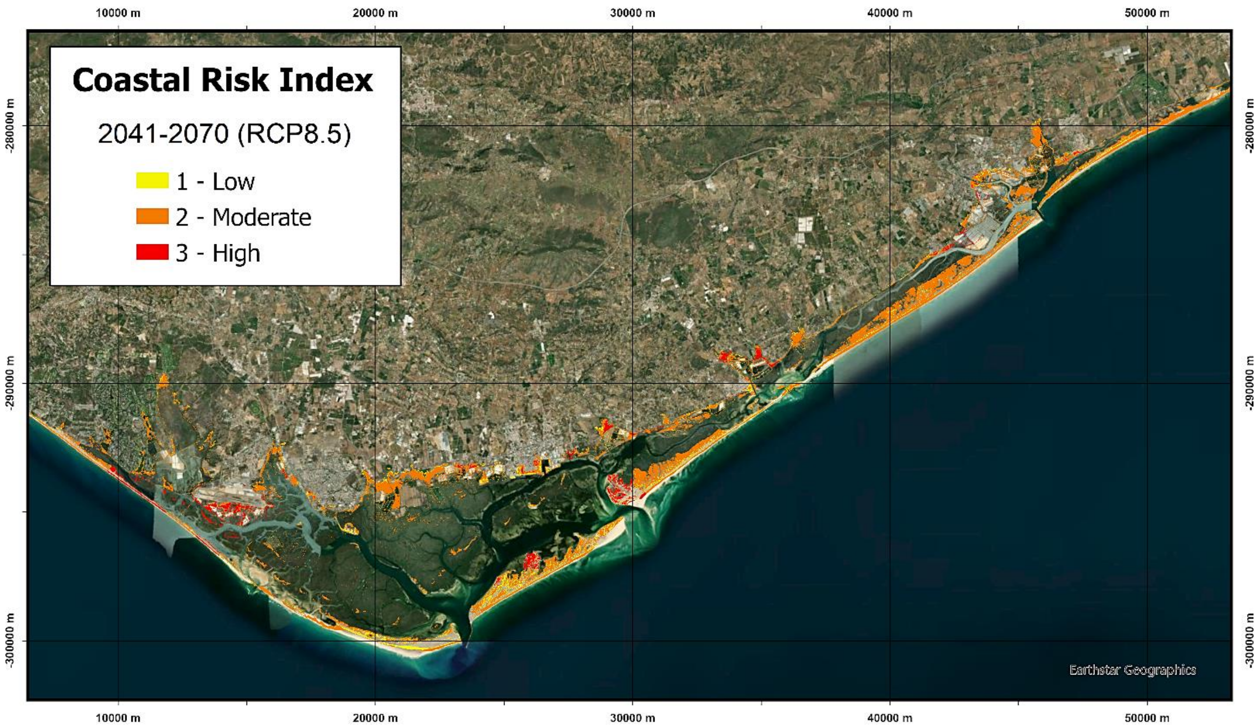


Figure 3.3.34 – Same as in Fig. 3.3.33, but for the RCP8.5 scenario.

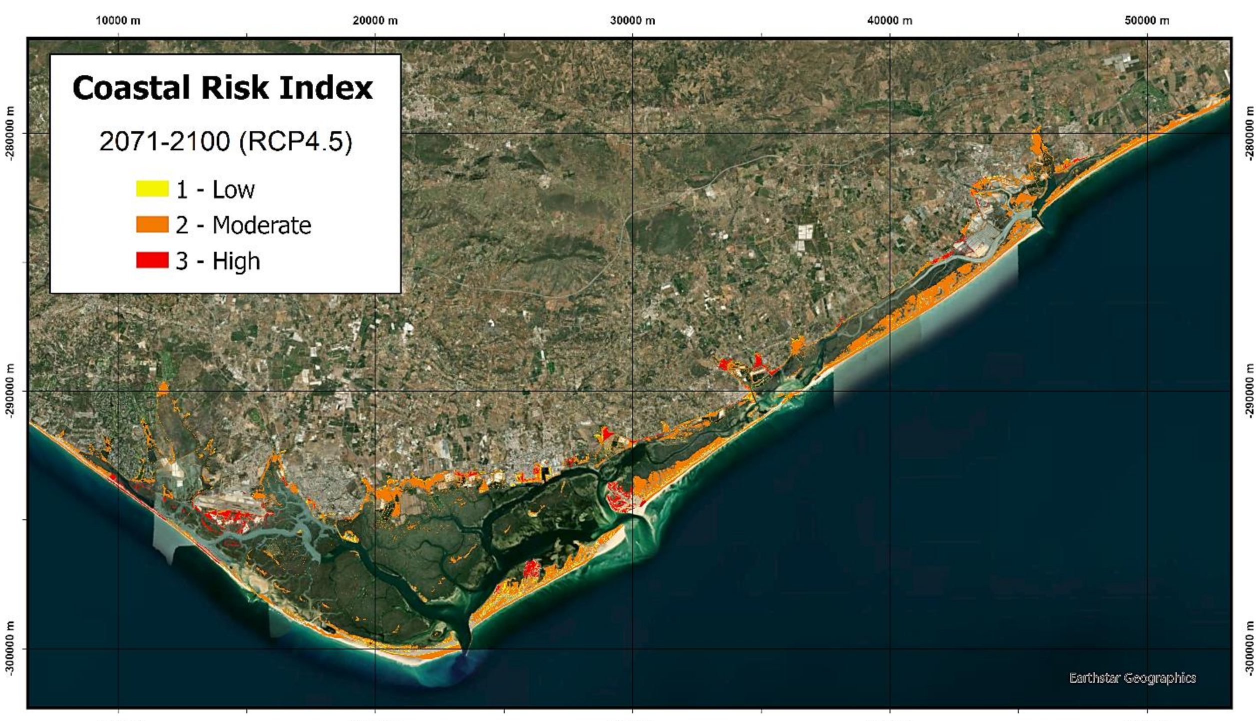


Figure 3.3.35 – Same as in Fig. 3.3.33, but by the end of the 2071-2100 future period.

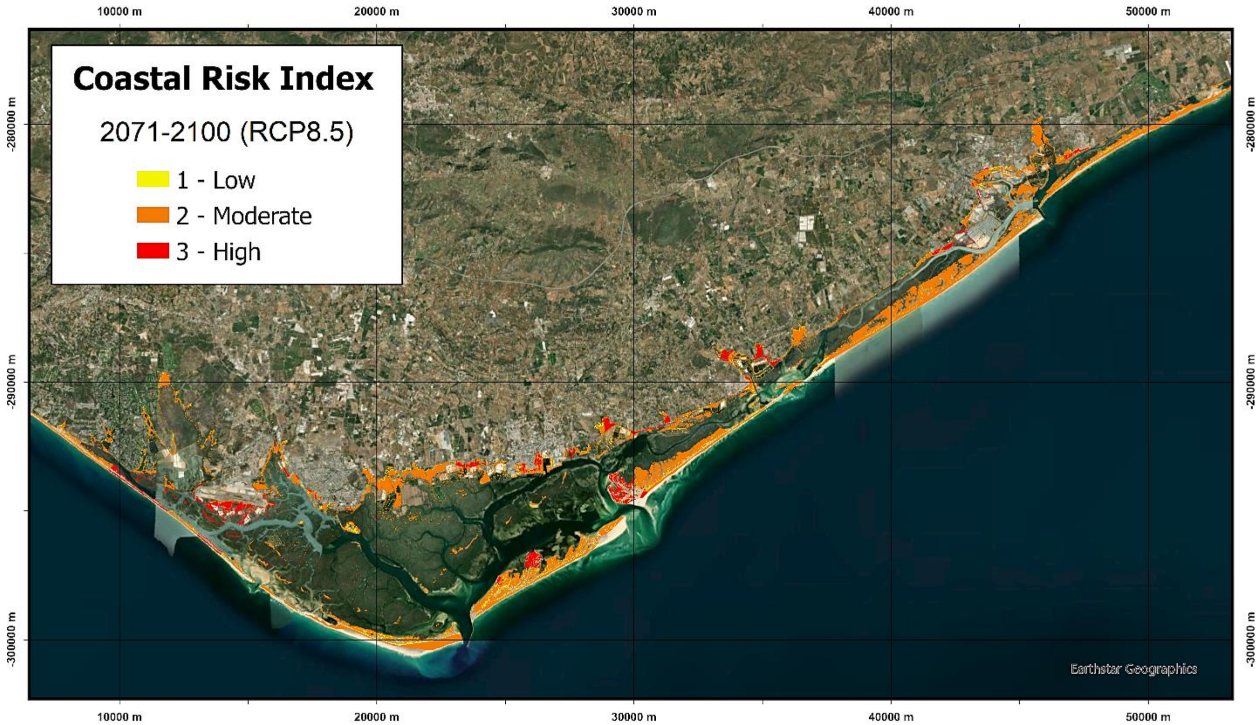


Figure 3.3.36 – Same as in Fig. 3.3.33, but by the end of the 2071-2100 future period under the RCP8.5 scenario.

In the Sado River estuary, near Setúbal (Figure 3.3.37 to Figure 3.3.40), the CRI generally assumes low to moderate (moderate to high) values by 2070 under RCP4.5 (2100 under RCP8.5). The coastal risk is especially high along densely populated coastal stretches (*e.g.*, Setúbal, Praias do Sado, Morgada) or in areas with high economic value (*e.g.*, Setúbal harbor).

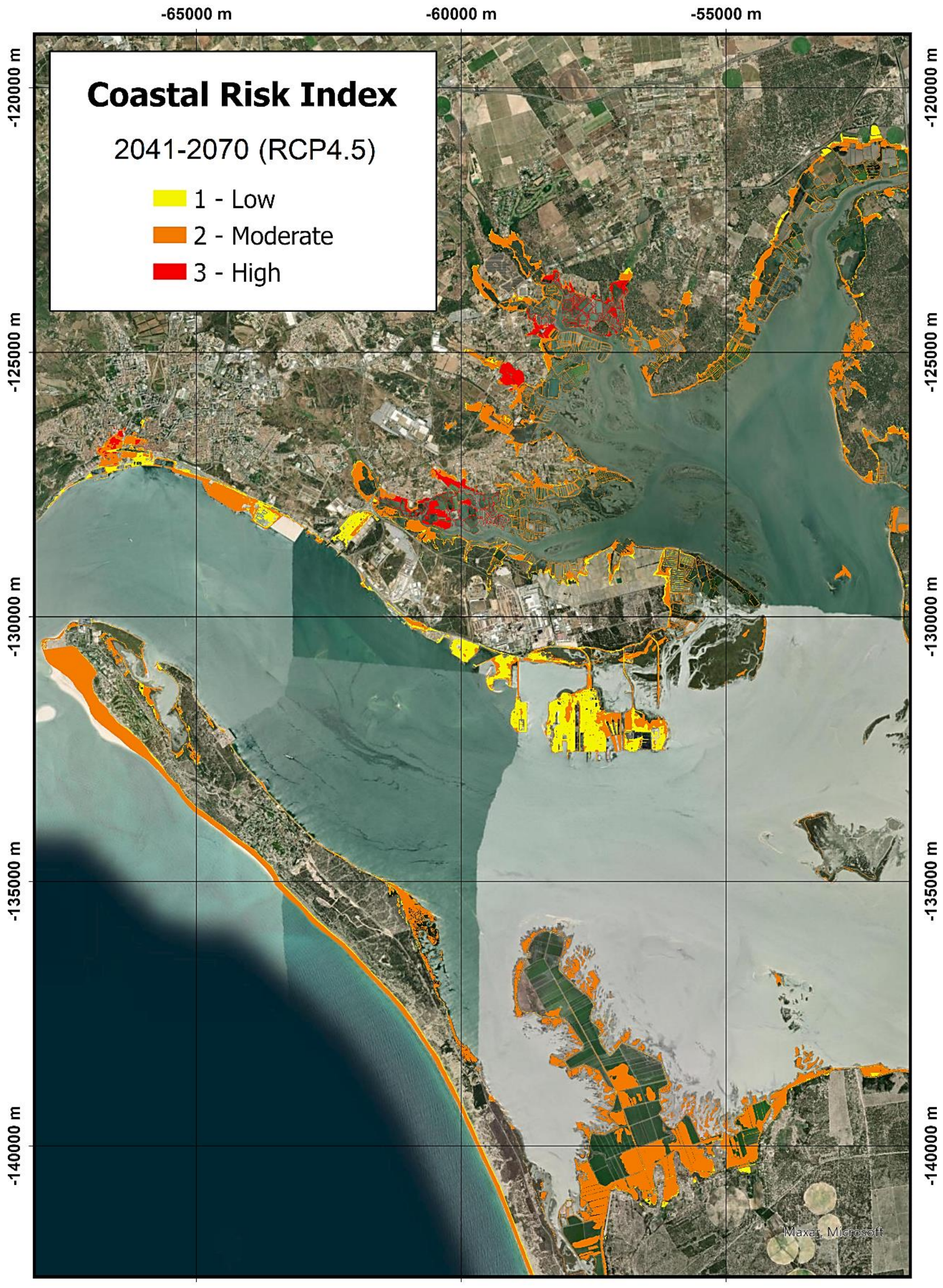


Figure 3.3.37 – Coastal Risk Index (CRI) for the Sado River estuary (Setúbal-Troia) region, by the end of the 2041-2070 future period, under the RCP4.5 scenario.

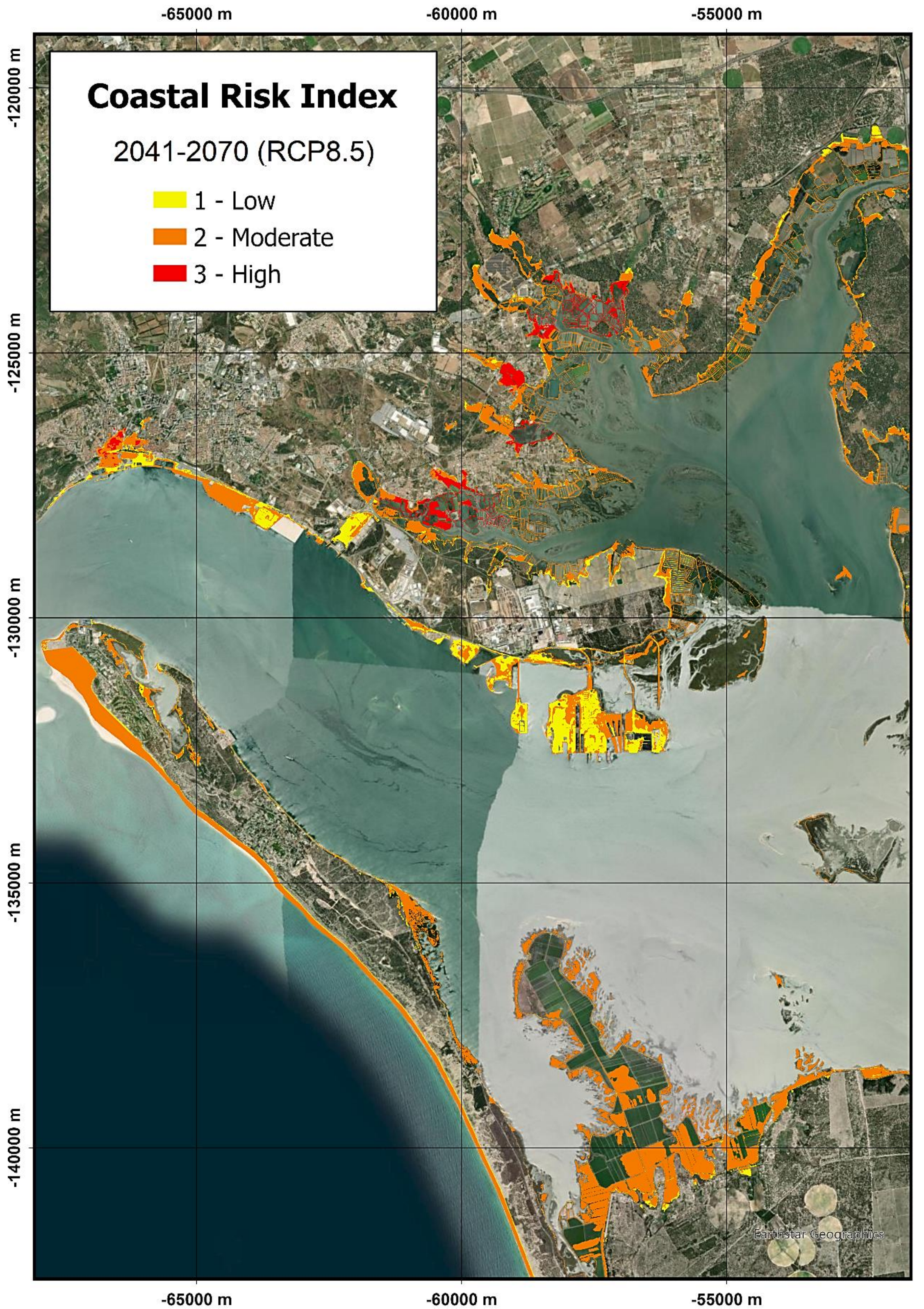


Figure 3.3.38 – Same as in Fig. 3.3.37, but for the RCP8.5 scenario.

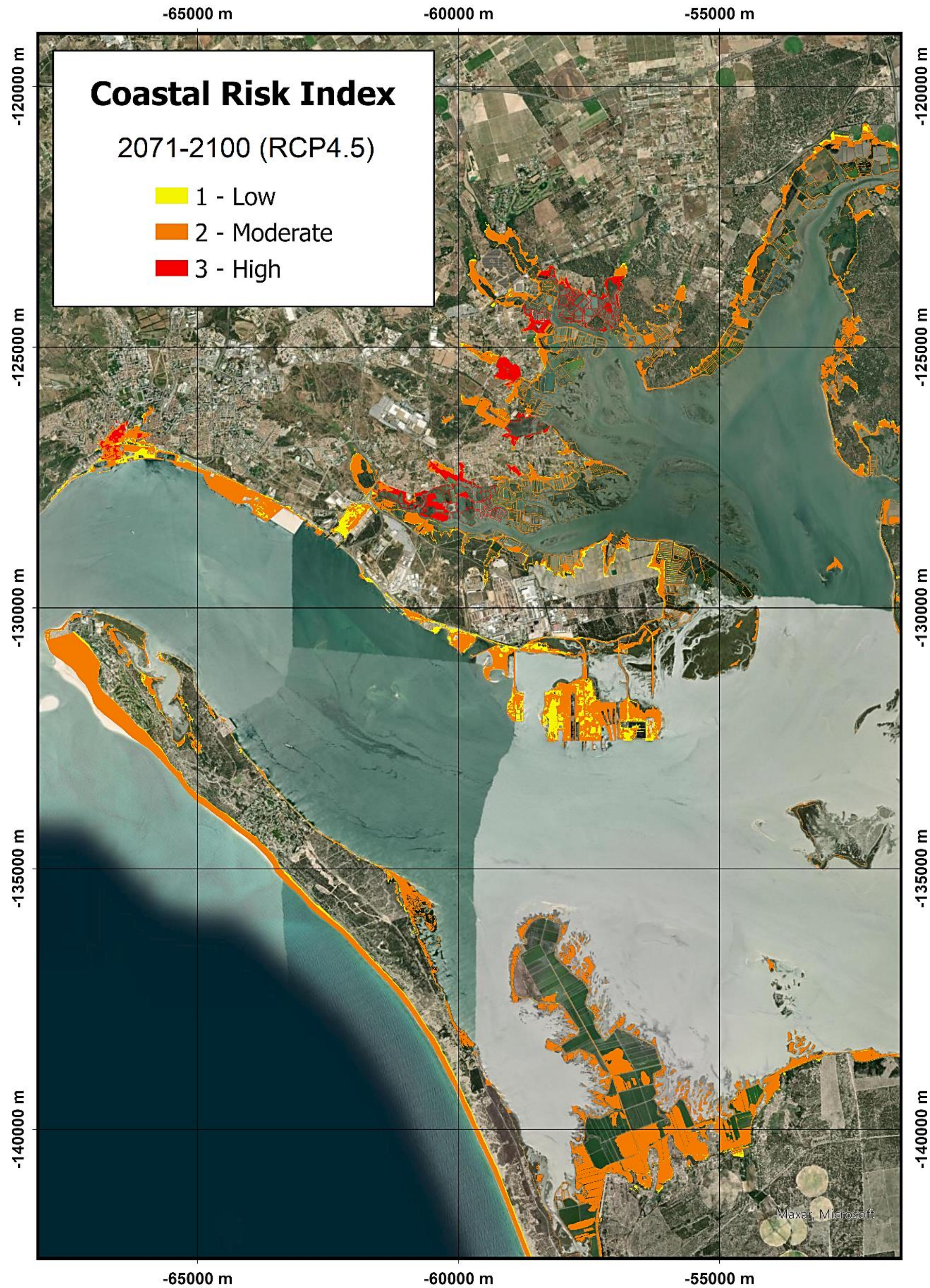


Figure 3.3.39 – Same as in Fig. 3.3.37, but by the end of the 2071-2100 future period.

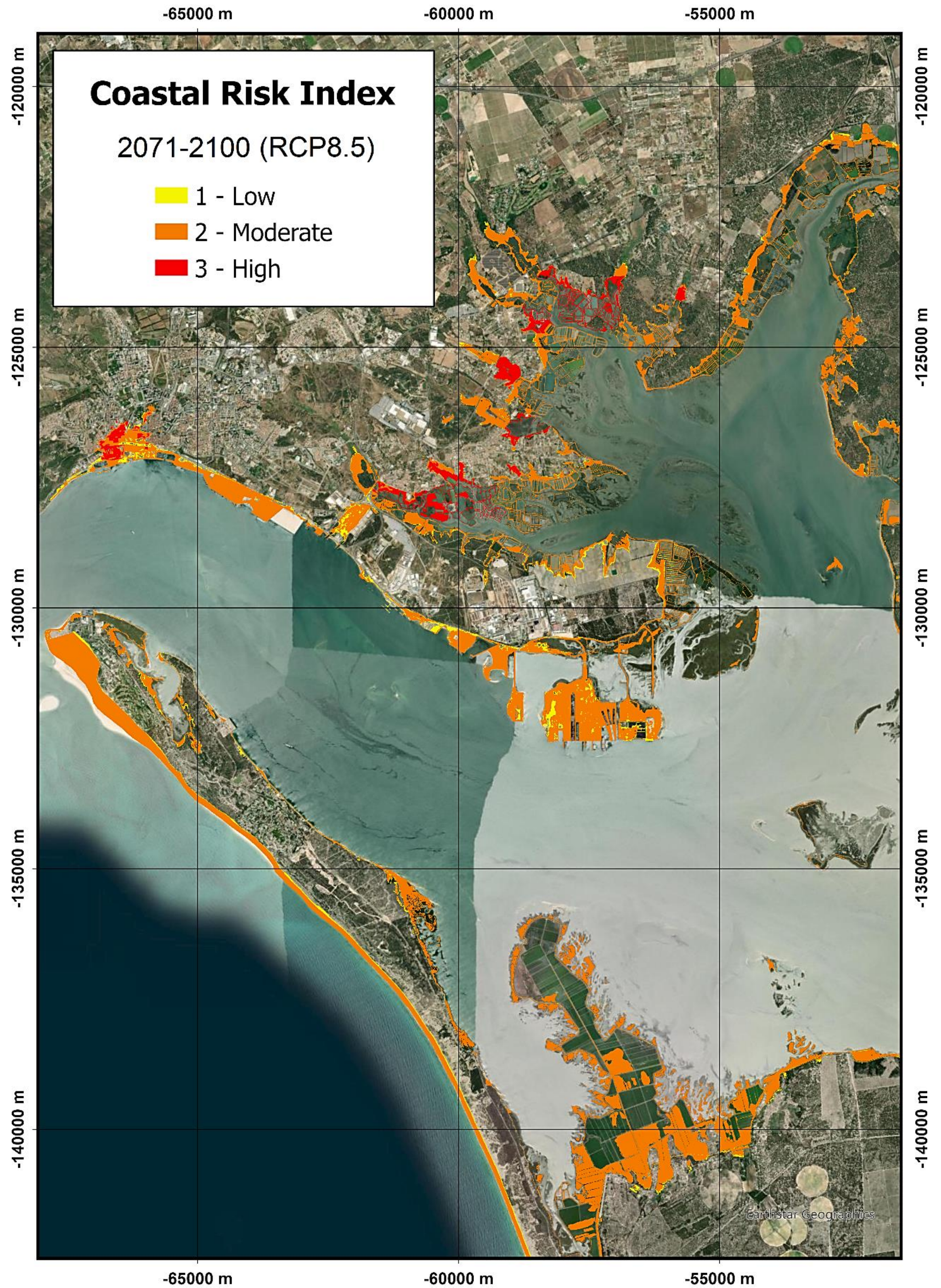


Figure 3.3.40 – Same as in Fig. 3.3.37, but by the end of the 2071-2100 future period under the RCP8.5 scenario.

In the Ria de Aveiro region (Figure 3.3.41 to Figure 3.3.44), the CRI generally assumes moderate to high values along densely populated coastal stretches (*e.g.* Costa Nova, São Jacinto, Aveiro – downtown, Ílhavo). Other relevant areas, such as the Aveiro harbor, exhibit low CRI for all future periods and scenarios.

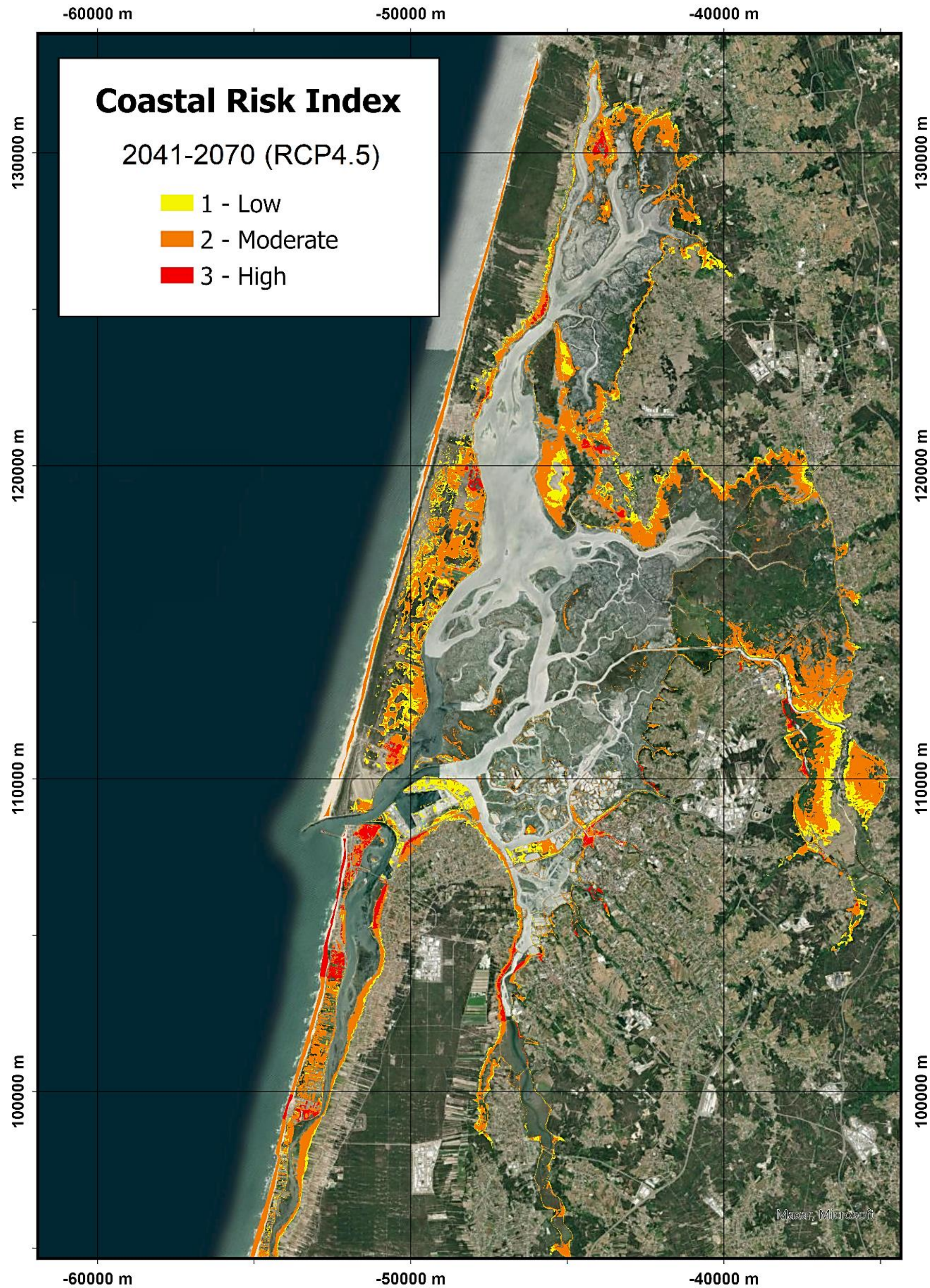


Figure 3.3.41 – Coastal Risk Index (CRI) for the Ria de Aveiro (Aveiro) region, by the end of the 2041-2070 future period, under the RCP4.5 scenario.

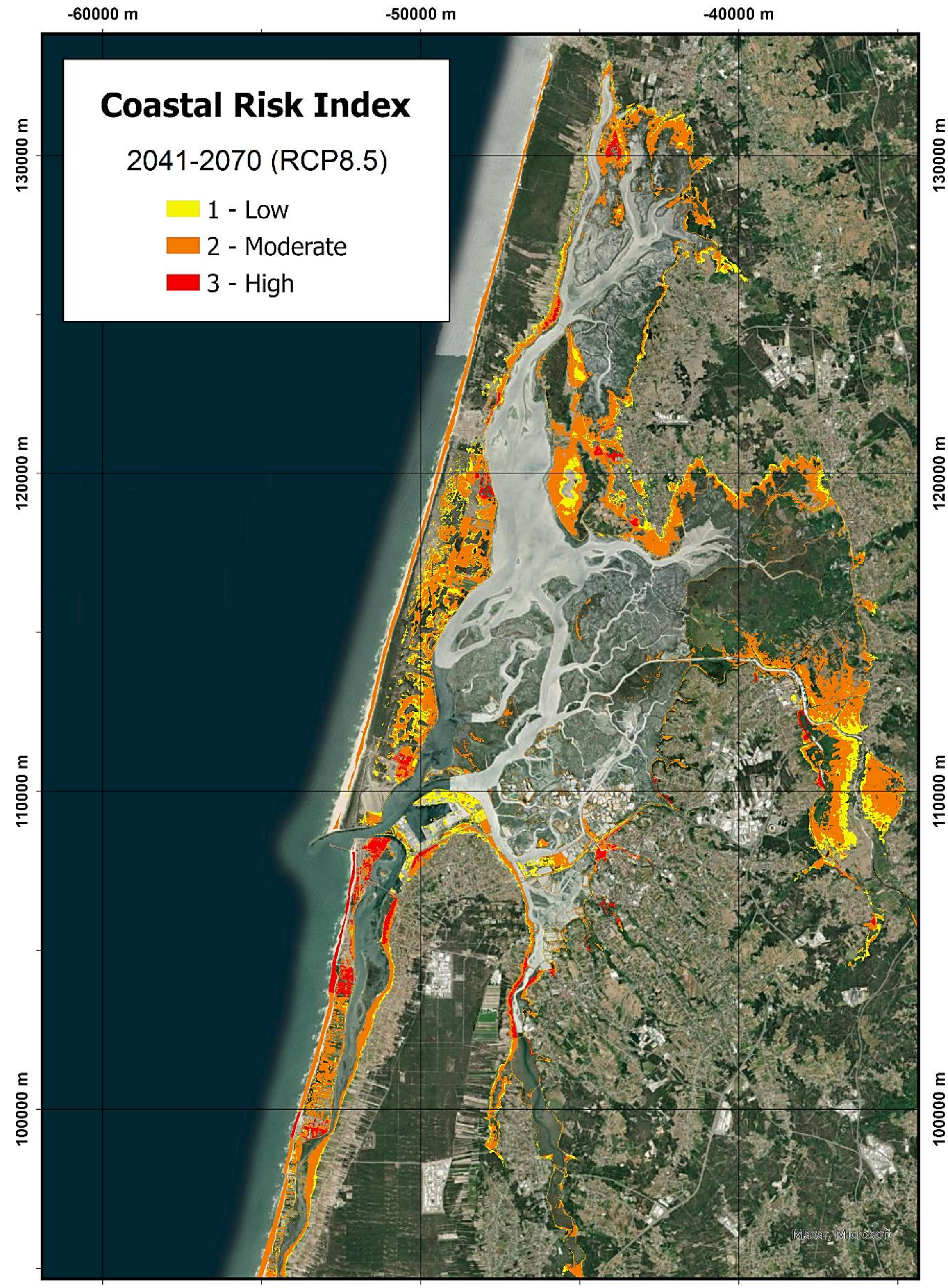


Figure 3.3.42 – Same as in Fig. 3.3.41, but for the RCP8.5 scenario.

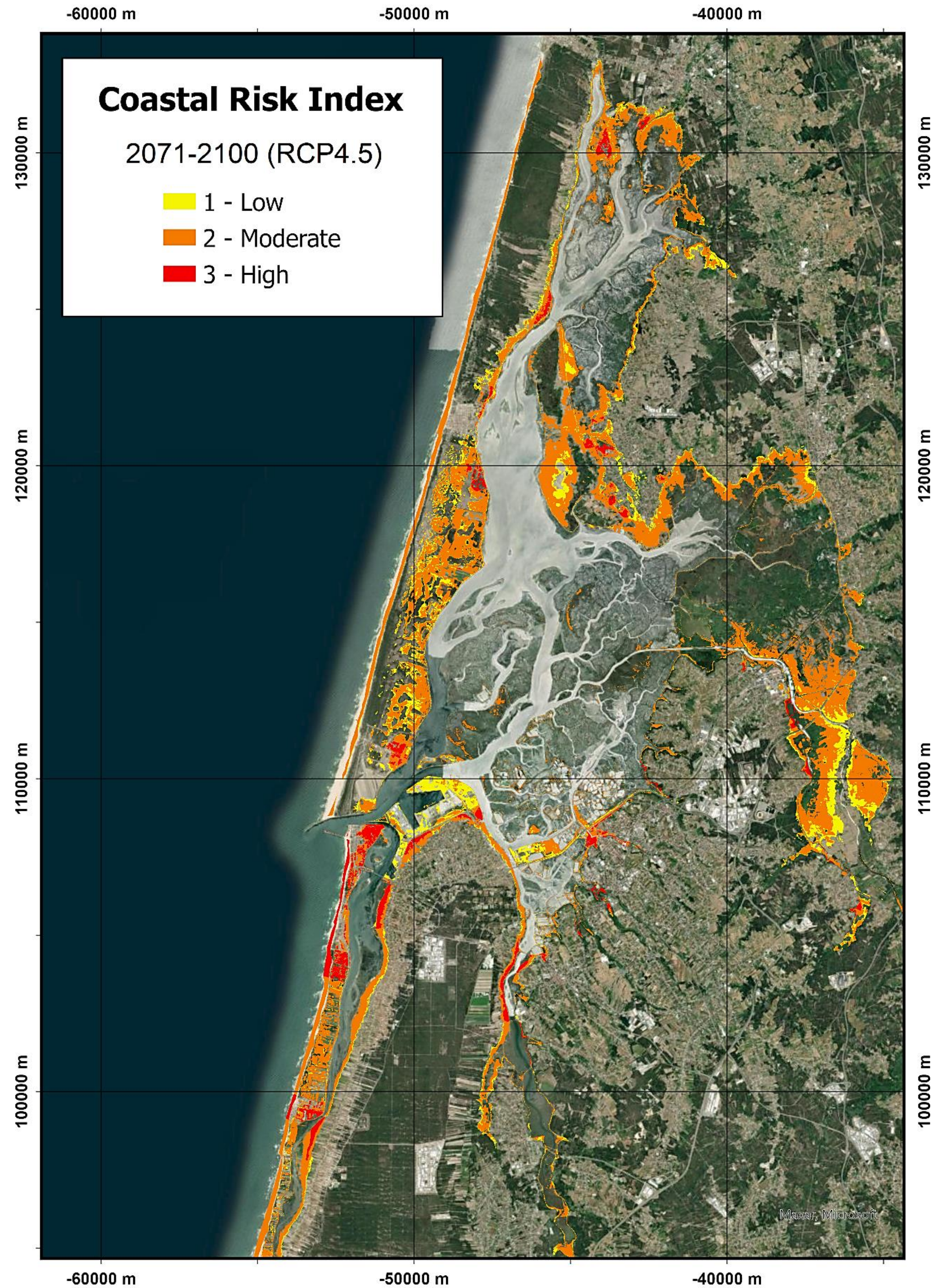


Figure 3.3.43 – Same as in Fig. 3.3.41, but by the end of the 2071-2100 future period.

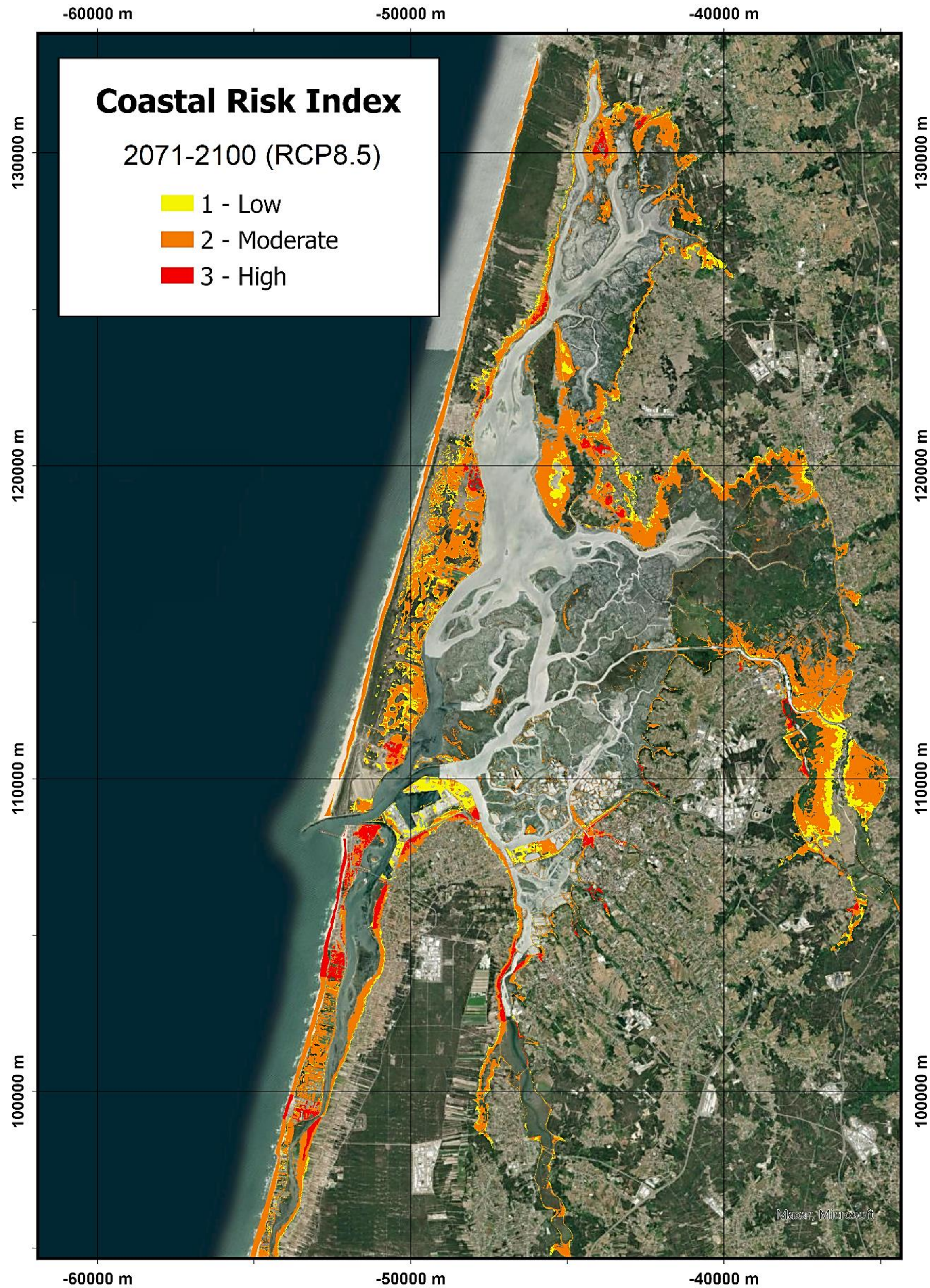


Figure 3.3.44 – Same as in Fig. 3.3.41, but by the end of the 2071-2100 future period under the RCP8.5 scenario.

In the Tagus River estuary, near Lisbon (Figure 3.3.45 to Figure 3.3.48), the CRI assumes moderate to high values considering all future periods and scenarios. The coastal risk is especially high along densely populated coastal stretches (*e.g.*, Alverca, Loures, Montijo, Moita) or in areas with high economic relevance (*e.g.*, the most productive areas in the Tagus estuary). High CRIs are also visible in the Costa da Caparica area (facing the ocean).

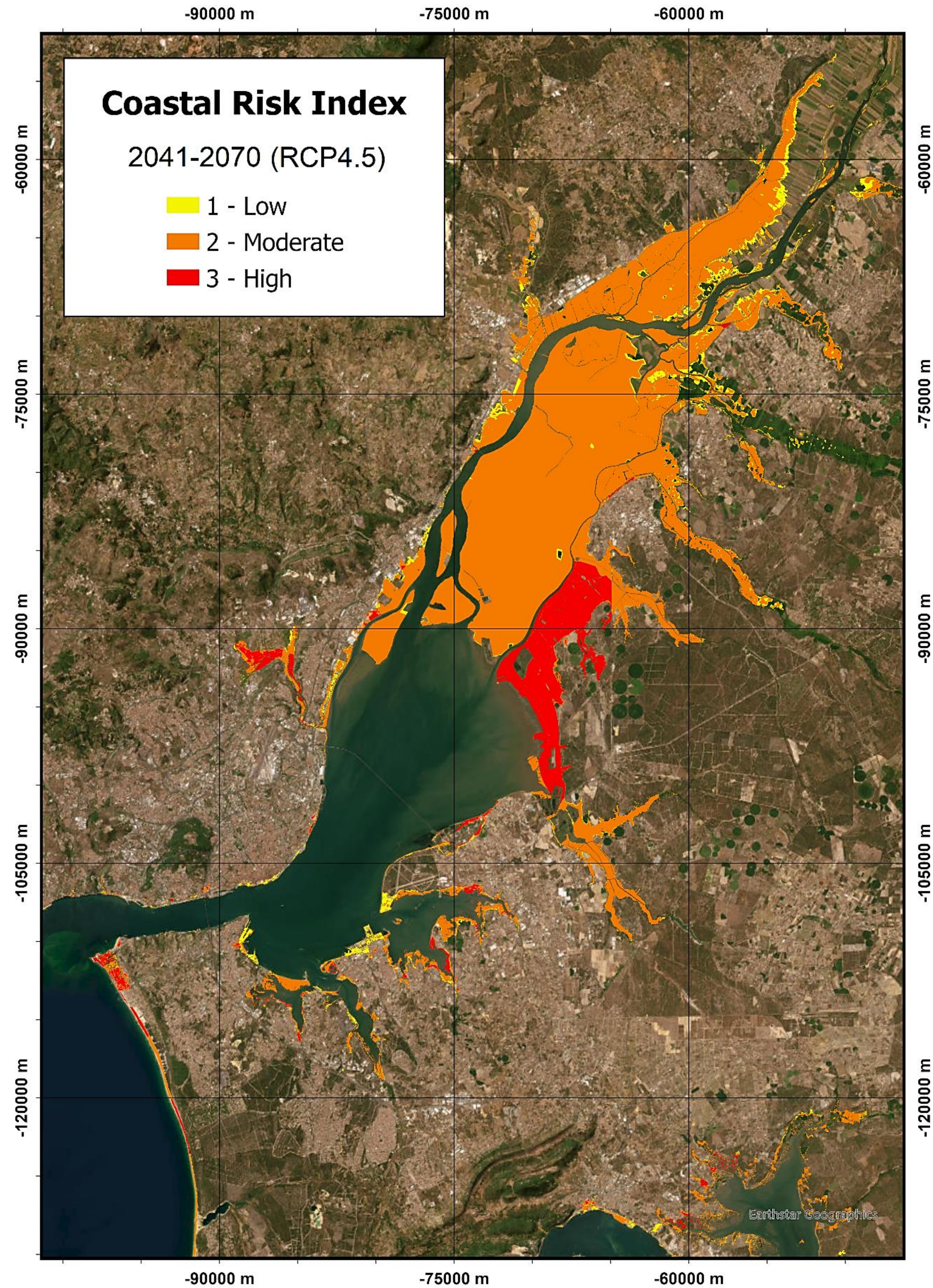


Figure 3.3.45 – Coastal Risk Index (CRI) for the Tagus River estuary (Lisbon) region, by the end of the 2041-2070 future period, under the RCP4.5 scenario.

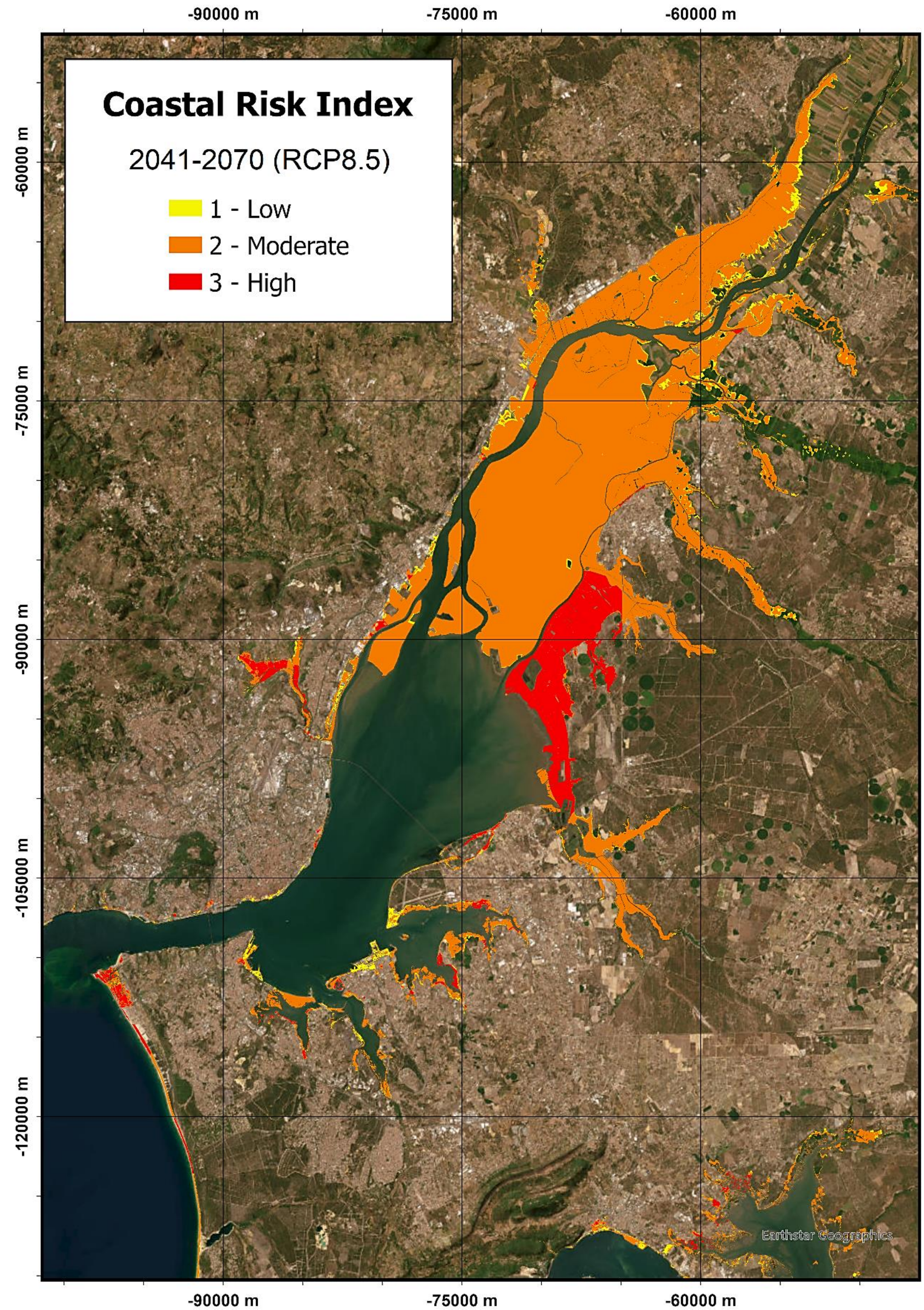


Figure 3.3.46 – Same as in Fig. 3.3.45, but for the RCP8.5 scenario.

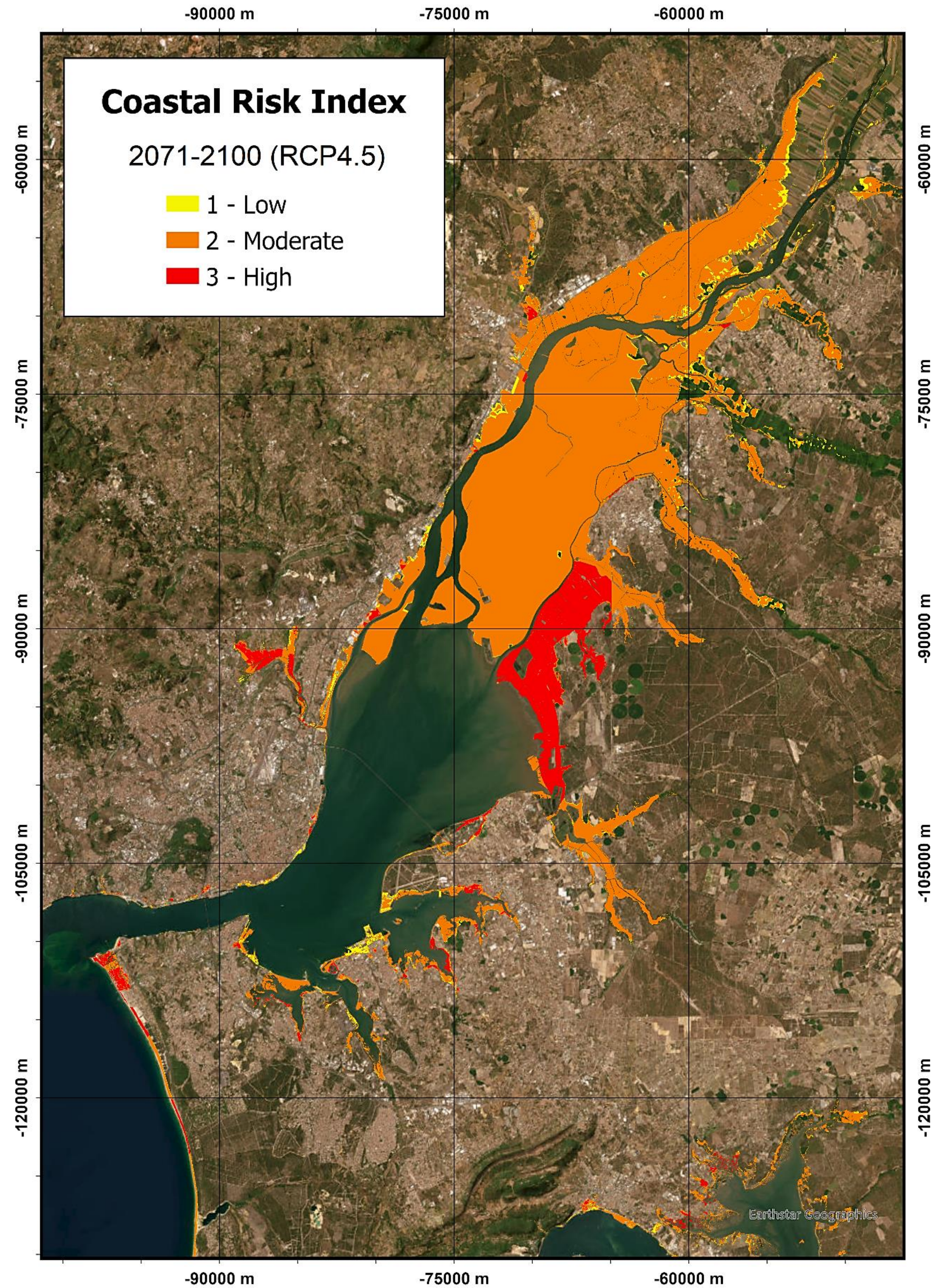


Figure 3.3.47 – Same as in Fig. 3.3.45, but by the end of the 2071-2100 future period.

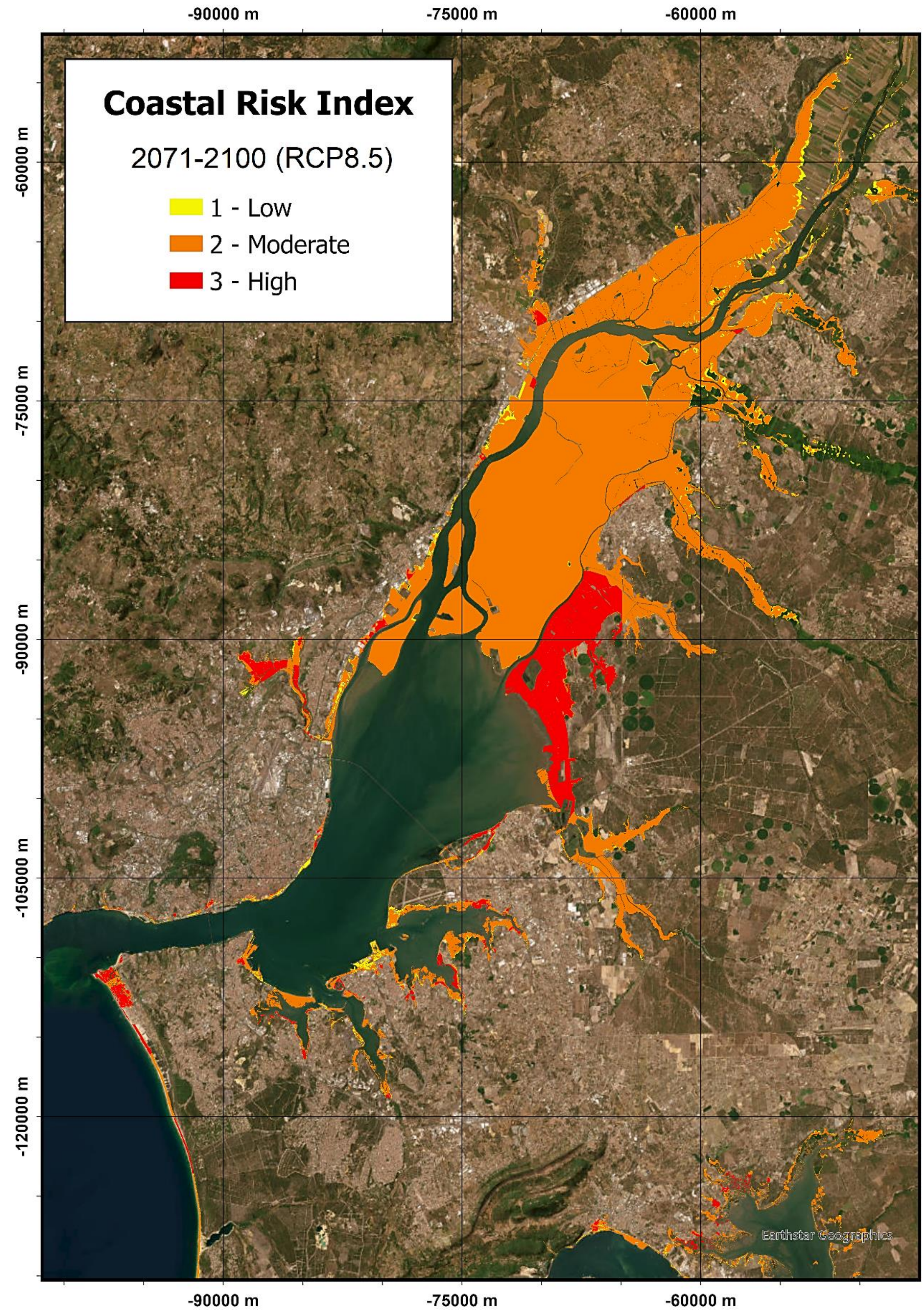


Figure 3.3.48 – Same as in Fig. 3.3.45, but by the end of the 2071-2100 future period under the RCP8.5 scenario.

A list of critical infrastructures potentially impacted due to their location within classified vulnerable areas is shown in Table 3.3.6, where each infrastructure is assigned an importance index ranging from 1 (low importance) to 3 (high importance).

Table 3.3.6 – CRI and Criticality Level (CL) related to economically and socially relevant infrastructures along the Portugal Mainland's coastlines. Only the limit scenarios and timeframes (2070 under RCP4.5 and 2100 under RCP8.5) are included.

Infrastructure	Typology	District	CRI (2100 - RCP8.5)	CRI (2070 – RCP4.5)	*Criticality* level (CL)	Weighted CL RCP8.5	Weighted CL RCP4.5
Aeródromo da Azambuja	Airfield	Lisbon	1,00	1,00	2,00	1,41	1,41
Aeródromo da Lezíria	Airfield	Lisbon	3,00	3,00	2,00	2,45	2,45
Aeródromo de Espinho	Airfield	Aveiro	1,00	<Null>	2,00	1,41	---
Aeródromo de Óbidos	Airfield	Leiria	1,00	1,00	2,00	1,41	1,41
Aeródromo do Alqueidão	Airfield	Lisbon	2,00	1,00	2,00	2,00	1,41
Aeródromo Municipal de Aveiro	Airfield	Aveiro	1,00	1,00	2,00	1,41	1,41
Aeródromo Municipal de Portimão	Airfield	Faro	3,00	3,00	2,00	2,45	2,45
Aeroporto Gago Coutinho	Airport	Faro	1,00	1,00	3,00	1,73	1,73
Ferragudo	Train stop	Faro	1,00	<Null>	1,00	1,00	---
Monte Gordo	Train stop	Faro	1,00	1,00	1,00	1,00	1,00
Pontes	Train stop	Setubal	2,00	1,00	1,00	1,41	1,00
Associação Náutica da Gafanha da Encarnação	Pier	Aveiro	2,00	1,00	1,00	1,41	1,00
Cais da Povoa de Santa Iria	Pier	Lisbon	2,00	1,00	1,00	1,41	1,00
Cais da Ribeira	Pier	Porto	1,00	1,00	1,00	1,00	1,00
Cais da Ribeira de Ovar	Pier	Aveiro	3,00	<Null>	1,00	1,73	---
Cais das Lavandeiras	Pier	Porto	3,00	3,00	1,00	1,73	1,73
Cais de Embarque de Moliceiros	Pier	Aveiro	3,00	3,00	1,00	1,73	1,73
Cais do Bico	Pier	Aveiro	3,00	3,00	1,00	1,73	1,73
Cais do Choupelo	Pier	Porto	3,00	2,00	1,00	1,73	1,41
Cais dos Pescadores Caminha	Pier	Viana do Castelo	1,00	1,00	1,00	1,00	1,00
Cais dos Pescadores de Sao Jacinto	Pier	Aveiro	3,00	3,00	1,00	1,73	1,73
Cais Palafitico do Samouco	Pier	Setubal	3,00	1,00	1,00	1,73	1,00
Centro Empresarial da Gafanha	Pier	Aveiro	3,00	2,00	1,00	1,73	1,41
Centro Nautico de Alges	Pier	Lisbon	3,00	3,00	1,00	1,73	1,73
Doca de Pesca da Afurada	Pier	Porto	2,00	1,00	1,00	1,41	1,00
Doca de Pesca de Vila do Conde	Pier	Porto	3,00	2,00	1,00	1,73	1,41
doca de pesca Porto de Leixoes	Pier	Porto	3,00	2,00	1,00	1,73	1,41
Doca Santa Luzia	Pier	Faro	3,00	3,00	1,00	1,73	1,73
Lisnave Almada	Pier	Setubal	3,00	2,00	1,00	1,73	1,41
Marina de Alhandra	Pier	Lisbon	1,00	<Null>	1,00	1,00	
Porto de Pesca Passeio Alegre	Pier	Porto	3,00	3,00	1,00	1,73	1,73
Porto de Pesca Povoa de Varzim	Pier	Porto	1,00	1,00	1,00	1,00	1,00
Terminal Cerealifero da Trafaria	Pier	Setubal	2,00	1,00	1,00	1,41	1,00
Terminal de Alandra - Terminal nº 15 do Porto de Lisboa	Pier	Lisbon	1,00	1,00	1,00	1,00	1,00
Terminal de Alandra (CIMPOR) - Terminal nº 17 do Porto de Lisboa	Pier	Lisbon	1,00	1,00	1,00	1,00	1,00
Terminal de Alandra (IBEROL) - Terminal nº 16 do Porto de Lisboa	Pier	Lisbon	1,00	<Null>	1,00	1,00	---
Xacobeo Transfer Ferry & Taxi Boat Caminha	Pier	Viana do Castelo	3,00	3,00	1,00	1,73	1,73
Alverca	Train station	Lisbon	2,00	2,00	2,00	2,00	2,00
Barreiro	Train station	Setubal	1,00	1,00	2,00	1,41	1,41
Belém	Train station	Lisbon	1,00	<Null>	2,00	1,41	
Bobadela	Train station	Lisbon	1,00	1,00	2,00	1,41	1,41
Cais do Sodré	Train station	Lisbon	2,00	1,00	2,00	2,00	1,41
Lagos	Train station	Faro	1,00	1,00	2,00	1,41	1,41
Praça do Quebedo	Train station	Setubal	3,00	3,00	2,00	2,45	2,45
Praias do Sado A	Train station	Setubal	1,00	1,00	2,00	1,41	1,41
Santa Iria	Train station	Lisbon	1,00	1,00	2,00	1,41	1,41
Vila Franca de Xira	Train station	Lisbon	1,00	1,00	2,00	1,41	1,41
Vila Real de Santo António	Train station	Faro	1,00	1,00	2,00	1,41	1,41
Cais da Lisnave	Shipyard	Setubal	3,00	1,00	3,00	3,00	1,73
Cais da Setenave	Shipyard	Setubal	1,00	1,00	3,00	1,73	1,73
Estaleiros de Vila do Conde	Shipyard	Porto	3,00	3,00	3,00	3,00	3,00
Estaleiros Navais de VIana do Castelo	Shipyard	Viana do Castelo	3,00	3,00	3,00	3,00	3,00
ETAR da Figueira da Foz	Water treatment station	Coimbra	3,00	2,00	2,00	2,45	2,00

Helitours Douro Azul	Heliport	Porto	1,00	1,00	1,00	1,00	1,00
Doca das Três Marias	Marina	Faro	3,00	3,00	1,00	1,73	1,73
Doca de Alcântara	Marina	Lisbon	1,00	1,00	1,00	1,00	1,00
Doca de Belém	Marina	Lisbon	1,00	1,00	1,00	1,00	1,00
Doca de Recreio das Fontaínhas	Marina	Setubal	3,00	3,00	1,00	1,73	1,73
Doca de Santo Amaro	Marina	Lisbon	2,00	2,00	1,00	1,41	1,41
Doca do Bom Sucesso	Marina	Lisbon	3,00	1,00	1,00	1,73	1,00
Doca do Clube Naval Setubalense	Marina	Setubal	1,00	1,00	1,00	1,00	1,00
Doca do Poço do Bispo	Marina	Lisbon	3,00	1,00	1,00	1,73	1,00
Doca dos Pescadores (Doca Pesca)	Marina	Setubal	3,00	3,00	1,00	1,73	1,73
Marina António Duarte Silva	Marina	Coimbra	1,00	1,00	1,00	1,00	1,00
Marina Clube da Gafanha	Marina	Aveiro	1,00	1,00	1,00	1,00	1,00
Marina da Póvoa de Varzim	Marina	Porto	1,00	1,00	1,00	1,00	1,00
Marina de Esposende	Marina	Braga	3,00	3,00	1,00	1,73	1,73
Marina de Faro	Marina	Faro	3,00	3,00	1,00	1,73	1,73
Marina de Lagos	Marina	Faro	3,00	1,00	1,00	1,73	1,00
Marina de Leça	Marina	Porto	1,00	1,00	1,00	1,00	1,00
Marina de Tróia	Marina	Setubal	1,00	1,00	1,00	1,00	1,00
Marina de Vilamoura	Marina	Faro	1,00	1,00	1,00	1,00	1,00
Marina do Clube de Vela Costa Nova	Marina	Aveiro	3,00	3,00	1,00	1,73	1,73
Marina dos Pescadores	Marina	Braga	3,00	3,00	1,00	1,73	1,73
Marina e Porto da Nazare	Marina	Leiria	3,00	1,00	1,00	1,73	1,00
Marina Parque das Nações	Marina	Lisbon	1,00	1,00	1,00	1,00	1,00
Marina Viana do Castelo	Marina	Viana do Castelo	3,00	3,00	1,00	1,73	1,73
Porto de Abrigo da Torreira	Marina	Aveiro	3,00	3,00	1,00	1,73	1,73
Porto de Pesca da Culatra	Marina	Faro	3,00	3,00	1,00	1,73	1,73
Porto de Recreio de Oeiras	Marina	Lisbon	1,00	1,00	1,00	1,00	1,00
Porto de Recreio de Olhão	Marina	Faro	3,00	3,00	1,00	1,73	1,73
Porto de Recreio do Carregal	Marina	Aveiro	1,00	1,00	1,00	1,00	1,00
Porto de Recreio do Guadiana	Marina	Faro	1,00	1,00	1,00	1,00	1,00
Porto de Recreio João Maria Conde	Marina	Lisbon	2,00	1,00	1,00	1,41	1,00
Porto Recreio de Olhão	Marina	Faro	1,00	1,00	1,00	1,00	1,00
Alfeite	Military	Setubal	3,00	3,00	3,00	3,00	3,00
Base Aérea Nº 6 - Montijo	Military	Setubal	1,00	1,00	3,00	1,73	1,73
Base Hidrográfica da Azinheira - Instituto Hidrográfico - Marinha	Military	Setubal	3,00	3,00	3,00	3,00	3,00
OGMA Indústria Aeronáutica de Portugal	Military	Lisbon	3,00	1,00	3,00	3,00	1,73
Porto de Viana do Castelo	Harbor	Viana do Castelo	2,00	1,00	3,00	2,45	1,73
Terminal de Cruzeiros de Lisboa	Harbor	Lisbon	3,00	1,00	3,00	3,00	1,73
Terminal de Cruzeiros Leixões	Harbor	Porto	1,00	1,00	3,00	1,73	1,73
Terminal Petrolífero do Porto de Leixoes	Harbor	Porto	2,00	1,00	3,00	2,45	1,73
Atlantic Ferries - Tróia (Cais Sul)	Maritime terminal	Setubal	1,00	1,00	2,00	1,41	1,41
Barco Taxi Alvor	Maritime terminal	Faro	1,00	1,00	2,00	1,41	1,41
Cais da Armona	Maritime terminal	Faro	3,00	3,00	2,00	2,45	2,45
Cais da Culatra	Maritime terminal	Faro	3,00	3,00	2,00	2,45	2,45
Cais das Portas do Mar	Maritime terminal	Faro	1,00	1,00	2,00	1,41	1,41
Cais de Cabanas	Maritime terminal	Faro	3,00	3,00	2,00	2,45	2,45
Cais de Olhão	Maritime terminal	Faro	3,00	3,00	2,00	2,45	2,45
Cais do Farol	Maritime terminal	Faro	3,00	2,00	2,00	2,45	2,00
Cais dos Vapores	Maritime terminal	Setubal	1,00	1,00	2,00	1,41	1,41
Cais Ilha da Fuseta	Maritime terminal	Faro	3,00	3,00	2,00	2,45	2,45
Ferry Boat São Jacinto	Maritime terminal	Aveiro	3,00	3,00	2,00	2,45	2,45
Ferry Praia de Faro	Maritime terminal	Faro	3,00	1,00	2,00	2,45	1,41
Ponte do Carvão	Maritime terminal	Faro	3,00	2,00	2,00	2,45	2,00
Terminal Ferry Ilha de Tavira	Maritime terminal	Faro	3,00	1,00	2,00	2,45	1,41
Terminal Fluvial da Trafaria	Maritime terminal	Setubal	2,00	1,00	2,00	2,00	1,41

Terminal Fluvial de Belem	Maritime terminal	Lisbon	3,00	3,00	2,00	2,45	2,45
Terminal Fluvial de Cacilhas	Maritime terminal	Setubal	3,00	2,00	2,00	2,45	2,00
Terminal Fluvial de Cacilhas	Maritime terminal	Setubal	3,00	2,00	2,00	2,45	2,00
Terminal Fluvial de Porto Brandao	Maritime terminal	Setubal	3,00	2,00	2,00	2,45	2,00
Terminal Fluvial do Barreiro	Maritime terminal	Setubal	1,00	1,00	2,00	1,41	1,41
Terminal Fluvial do Cais do Sodré	Maritime terminal	Lisbon	1,00	1,00	2,00	1,41	1,41
Terminal Fluvial do Montijo	Maritime terminal	Setubal	2,00	1,00	2,00	2,00	1,41
Terminal Fluvial do Seixal	Maritime terminal	Setubal	3,00	1,00	2,00	2,45	1,41
Terreiro do Paço - Terminal Fluvial	Maritime terminal	Lisbon	1,00	1,00	2,00	1,41	1,41

3.3.2. Adaptation measures

Along coastal areas, plans to adapt to climate change are essential to address the likely growing threats posed by rising sea levels, potentially increased storm intensity, changes in wave energy and direction, as well as and other climate-related challenges that will impinge coastal areas. These plans typically involve a combination of policy, engineering, and environmental management measures to mitigate and adapt to the impacts of climate change. To avoid excessive future losses, particularly in the light of projected climate change impacts, coastal zone managers have various instruments at their disposal. These primarily concern land-use planning (establishing buffer zones/setback zones) and engineering solutions (beach nourishment and coastal protection).

Coastal adaptation lines of action can be consubstantiated on different strategies to be applied by coastal managers. Among those, we summarize below the ones that are more frequently applied:

1) **Coastal Protection and Infrastructure:**
   - Building and enhancing coastal defences such as seawalls, dykes, and levees to protect against SLR and storm surges;
   - Elevating critical infrastructure and buildings in flood-prone areas to reduce the risk of inundation;
   - Implementing beach nourishment and dune restoration projects to protect coastlines from erosion.
2) **Climate-Resilient Building Codes and Zoning**:
   - Developing and enforcing building codes that consider the impacts of climate change and ensure that new construction is resilient to flooding and other climate-related risks.
   - Implementing zoning regulations that restrict development in high-risk areas and encourage sustainable land use practices.

3) **Risk Assessment and Early Warning Systems**:
   - Conducting risk assessments to identify vulnerable areas and prioritize adaptation efforts.
   - Developing and maintaining early warning systems to provide timely alerts for approaching storms and rising sea levels, allowing residents to take protective measures.
4) **Natural Infrastructure and Ecosystem Restoration**:
   - Promoting the restoration of natural ecosystems, such as wetlands, that provide natural buffers against storm surge and erosion.
   - Creating and preserving natural barriers that can absorb floodwaters and reduce damage to coastal areas.
5) **Sustainable Land Use and Retreat**:
   - Encouraging sustainable land use and urban planning practices that limit development in high-risk areas and promote the use of green infrastructure.
   - Planning for managed retreat in areas where adaptation measures are not feasible, gradually relocating communities away from high-risk coastal zones.
6) **Public Education and Outreach**:
   - Educating and engaging coastal communities about the risks associated with climate change and the importance of adaptation strategies.
   - Encouraging residents to take individual action to prepare for and respond to coastal hazards.
7) **Collaboration and Funding**:
   - Collaborating with neighbouring jurisdictions and governments to coordinate efforts and share resources.
   - Securing funding from various sources, including federal and state government grants, to support the implementation of adaptation projects.
8) **Research and Monitoring**:
   - Continuously monitoring SLR, storm patterns, and other relevant climate indicators to update adaptation strategies as needed.
   - Supporting scientific research to better understand local climate impacts and adaptation measures and costs.

Over recent years there has been a great development in the search for sustainable and more environmentally balanced solutions to adapt to coastal hazards. Among these, nature-based solutions for coastal adaptation are often cost-effective and can provide multiple benefits, including improved biodiversity, recreational opportunities, and water quality. They complement traditional engineering solutions and help create more resilient and sustainable coastal environments in the face of climate change.

These approaches are increasingly recognized as valuable tools in climate adaptation and are being integrated into national and international climate strategies and policies. However, nature-based solutions have rarely been taken into account in adaptation strategies, despite the services and benefits they provide. Nature-based solutions are actions to protect, sustainably manage and restore natural and modified ecosystems in ways to address societal challenges effectively and adaptively, to provide both human well-being and biodiversity benefits. Nature-based solutions can potentially adapt more easily to climate change impacts, in comparison to hard solutions that cannot always be modified to address sea level rise, require maintenance and may create erosion in other places. By reducing the intensity of waves and impacts caused by storms, and by retaining sediments, Nature-based Solutions are invaluable allies in adapting to sea level rise, at a low cost.

Coastal adaptation through nature-based solutions involves using natural ecosystems and processes to address the challenges posed by climate change and protect coastal areas. These solutions leverage the inherent resilience and ecological benefits of natural environments to enhance the adaptive capacity of coastal regions. Here are some key examples of nature-based solutions for coastal adaptation:

1) **Salt Marsh Restoration**: Salt marshes provide valuable protection by absorbing floodwaters and reducing erosion. Restoring and preserving salt marshes can enhance coastal resilience. Nevertheless, the impact of permanent flooding resulting from SLR on the currently existing salt marshes must be taken into account before considering their restoration.
2) **Living Shorelines**: Constructing living shorelines using native vegetation, oyster reefs, and other natural features helps stabilize the coastline and provides habitat for wildlife. These structures are more resilient than traditional hardened structures.
3) **Dune Restoration**: Natural sand dunes act as barriers against storm surges and erosion. Restoring and nourishing dunes can enhance coastal protection while preserving recreational areas.
4) **Wetland Creation and Restoration**: Constructing or restoring wetlands in coastal areas can help absorb excess water during storm events, reduce flooding, and enhance biodiversity.
5) **Beach Nourishment**: Adding sand or sediment to eroded beaches can be a nature-based solution to counteract the effects of SLR and erosion while maintaining recreational areas.
6) **Integrated Coastal Zone Management** (ICZM): Developing comprehensive plans that take into account natural and human systems in coastal areas, considering the use of natural features and habitats to protect against climate-related hazards.
7) **Erosion Control through Vegetation**: Planting and maintaining native vegetation in coastal areas can stabilize soil and reduce erosion, acting as a natural defence against SLR.

8) **<u>Habitat Protection and Conservation</u>**: Preserving and protecting coastal habitats and ecosystems, such as sand dunes, seagrass beds, and salt pans, can contribute to coastal resilience by maintaining natural features.

Adaptation to coastal hazards under a climate change scenario must be addressed by combining the application of these different strategies. Portugal with its diversified coastal settings requires the careful selection of tailored solutions for specific areas.

Most European Union Member States and regional governments have developed adaptation strategies for their coastal areas. Within the European Union (EU), the challenge of adaptation to climate change in coastal areas has been addressed on several occasions. Firstly, in 2002, the European Parliament and the Council adopted a recommendation on the implementation of an integrated coastal zone management strategy in Europe, particularly with regards to the threat to coastal zones and the effects of climate change. Thus, the European Union formulated eight principles to be considered considering the elaboration of national strategies for integrated coastal zone management. Notably the aspects of a broad global perspective taking into account the interdependence and disparity of natural systems and human activities as well as a long-term perspective based on the precautionary principle and the needs of present and future generations. Under the 2007 EU Flood Directive on the assessment and management of flood risks, Member States were obliged to assess rivers and coastlines for flood risk, map the areas at risk and assess the populations at risk in order to take adequate measures to reduce these risks (https://environment.ec.europa.eu/topics/water_en). Following the same line of thought, the OECD (2022) also recommended that, in view of the diverse and often conflicting uses of and pressures on coastal zone resources, its member countries should employ policy instruments, individually or in combination, in integrated coastal zone planning and management, including:

- Collection and updating of relevant information, and development of coastal environment indicators to guide planning and monitoring of coastal zone activities and processes;
- Establishment of environmental objectives for: land use planning and zoning, coastal waters planning (including inland waters, semi-enclosed seas, estuaries), conservation requirements, ecosystem protection and restoration, discharge limits, water quality for receiving waters and waters flowing into the coastal zone, and control and reduction of inputs from polluting and hazardous substances;
- Establishment and maintenance of monitoring and enforcement procedures for environmental objectives and targets;
- Environmental assessment incorporating economic and social criteria;

- Public education and participation in decision-making at an early stage of policy formulation and project assessment, and adoption of wider public participation procedures;
- Application of regulations and economic instruments within the framework of the Polluter Pays Principle, and pricing coastal zone resources to reflect social costs of use and depletion;
- Where appropriate, enactment of national legislation to enforce coastal zone management objectives.

Currently, the Portuguese legal framework, summarized by Schmidt et al., (2013) - Figure 3.3.49, provides an intricate, unclear and sometimes overlapping coastal governance scheme. Schmidt et al., (2013) identifies three dysfunctional features on the Portuguese legal structural coastal governance: 1) Lack of policy clarity and disjointed continuity backed by an insufficient and unreliable political will; 2) Difficulty in coordinating institutions and interested stakeholders; 3) Weak and ineffective science. On this last topic, Schmidt et al., (2013) describes an underachievement in the integration of scientific knowledge within coastal policies, which still lack important data (for instance identifying risky zones for planning avoidance through reliable assessment of coastal erosion and climate change risks). Despite several consistent efforts over the last decade (*e.g.*, APA's COSMO monitoring program, APA's CHIMERA project for identifying borrow areas for artificial beach nourishments in the continental shelf, and the revision/update of some POC's) there is still a need to reinforce bridges that can strengthen and interlink advanced scientific knowledge and its swift use and application on the coastal legal framework and on the daily practices of coastal managers. In fact, the Portuguese government has developed and continues to update its National Strategy for Climate Change (ENAAC) and National Adaptation Plan (PNAAC), which outline the country's approach to adapting to climate change, including coastal areas.

Laws, plans and strategies	Institutions and responsibilities	Commentaries on adaptive governance
Public Maritime Domain – PMD (Decree Dec 31, 1864): coastal strip subject to State ownership	– PMD: Navy	**Difficulty in coordinating institutions and interested stakeholders**: The Navy and later the Ports General Directorate had total autonomy over coastal management and defence, with an artificial and "engineering" vision of the coast – "hold the line"; it was a top-down and authoritarian approach; environmental safeguards were nearly absent
Recognition of Risk		
DL 1971 establishes a strip of 50 m as PMD and creates an "adjacent zone" with restricted occupation; further prevention from coastal risks	– DL 1971 – Ministries of Public Works and Navy; the Ports Directorate (1971) assumes jurisdiction on the coast	**Lack of political clarity**: In this phase we identify a fist symptom of recognition of coastal/environmental risks, following a number of disastrous events with human losses; the constant construction of groynes; but environmental management for its own is still not present in the governance/institutional model
Municipal Spatial Plans (MSP/PDM) (1982, later ruled by DL 69/90) **Creation of many protected areas on the coast and the Ecologic National Reserve** (1983, later ruled by DL 90/93), including a coastal strip (30 m) where any construction and/or destruction of vegetation is prohibited. DL 302/90 establishes the principles to be followed on coastal zones	– Coastal municipalities (50); Ministry of Planning and Territory Management – REN: Secretary of State for the Environment – PMD – Special commission (coordinated by the Navy and created in 1984): binding judgements on occupation	**Lack of policy clarity and reliable political will**: Despite having been created in the 1980s, MSP were ruled only 10 years later and implemented in 1995 (DL 60/90); until then there wasn't planning on the coastline and construction spread without any rules (in contradiction with REN, also ruled almost a decade after its creation – DL 90/93); great controversy with municipalities and their construction pledges. **Lack of reliable political will**: MSP and REN – basically reactive measures which proved largely ineffective; **Lack of policy clarity**: PMD commission still in charge (Navy), in spite of the transfer of coastal defence to the Environment Ministry; Creation of multiple protected areas on the coast; some demolitions occur in REN coastal zones at this time.
Critical Analysts		
Shoreline Management Plans (1993) – POOCs (DL 309/93) – special spatial plans ruling uses and activities in the coastal zones and promoting nature protection and landscape qualification; jurisdiction over strip up to 500 m, covering 9 coastal stretches in the Portuguese mainland	– Creation of Ministry of Environment (1990) and Water National Institute (INAG, 1993); Directorate for Natural Resources replaces Ports Directorate (DL 201/92) on the coast (except for harbours) – Implementation of POOCs: regional delegations of the Ministry of Environment, (50 m), municipalities (450 m) and Nature Conservation Institute (ICN) for protected areas.	INAG stops plans to build groyne fields all over the coast; preference for soft interventions. **Weak and ineffective science and difficulty in coordinating institutions**: POOCs faced many constraints: lack of resources and subsequent failure in getting good background data; exclusion of certain areas as harbours; too many institutions in charge and weak coordination. (Veloso-Gomes & Taveira-Pinto, 2003). **Lack of policy clarity and reliable political will**: Despite having jurisdiction over the rest of spatial plans ("special plans"), they only started 10 years after municipal ones. And by then many construction areas had already been approved.
Framework Law for Spatial Planning (Law 48/98)	– Min. of Equipment, Planning and Territory Management	**Lack of policy clarity and reliable political will**: the framework law for spatial planning intended to put POOC on the top of the hierarchy, over municipal plans, but it only started a "war" of competencies between local, regional and national institutions.
Litoral Programme (1998): mention to the development of an integrated and coordinated coastal management; was also meant to improve the juridical, administrative and legal system.	– Litoral Programme: Ministry of Equipment, Planning and Territory Management; INAG; ICN and regional environmental delegations.	**Lack of policy clarity and reliable political will**: The Littoral programme was a mere resolution from the council of ministers, not an actual strategy; outcomes were very limited (Carneiro, 2007).
Polis Programme (DL 26/2000) – 8 coastal urban qualification projects	– Polis: Ministry of Environment and Spatial Planning; municipalities; Parque Expo (public-private partnership)	**Lack of policy clarity and difficult coordination between institutions**: Since 2000, Polis projects also became in charge of POOCs, overlapping with the institutions already on the field, changing and delaying plans.

Figure 3.3.49 – Portuguese coastal laws, plans and strategies (Schmidt et al., 2013).

In Portugal, since the 1990s the development of Integrated Coastal Management (ICM) has stimulated a more integrative and participative approach to coastal management, with the government developing legislation for coastal zone protection, recovery, management, and governance (Oliveira et al., 2020). Laws and management tools link terrestrial, water, and maritime issues with coastal management (Figure 3.3.50).

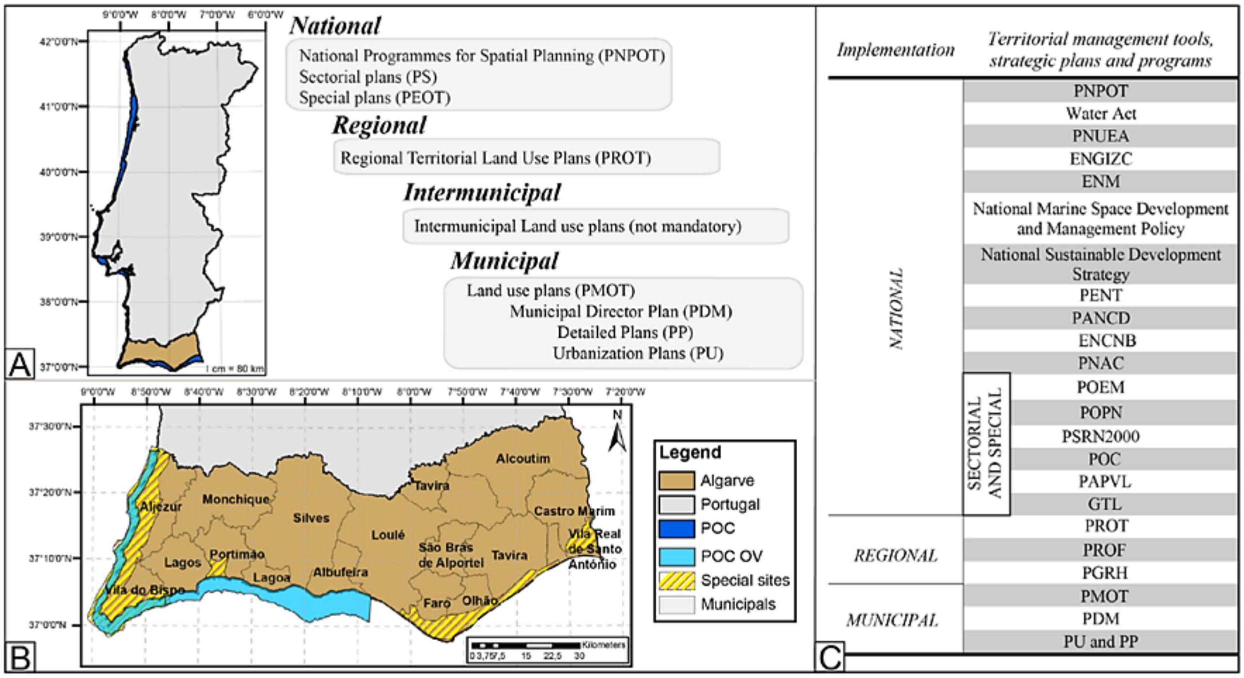


Figure 3.3.50 – Portuguese coastal law framework and legislative edifice (Oliveira et al., 2020).

The path developed by Portuguese central, regional, and local entities will be important to minimise risk situations (for people and assets) and enhance the protection and sustainable development of coastal areas. Application of the national strategy has taken its first steps, but clarity and communication are key aspects for the future ICZM implementation. It is noteworthy that the implementation of management decisions and directives usually takes very long, not only due to bureaucracy and the governmental system, but also due to the lack of knowledge and understanding among the general population that interventions like demolition of buildings at risk are necessary (Oliveira et al., 2020). Some of these problems have been partially addressed in several Action Plans, the most recent being the *Litoral XXI* Action Plan, which has replaced the *Plano de Acção e Protecção do Litoral* (PAPVL) identified in Figure 3.3.50. The *Litoral XXI* provides the basis for programming interventions in coastal areas based on priority levels. It incorporates information from different plans and strategies related with water, hydrographic basins, coastal areas, territorial protection and enhancement, climate change and dredging operations, as well as the conclusions of *Grupo de Trabalho do Litoral* (Santos et al., 2014) and *Grupo de Trabalho dos Sedimentos* (Andrade et al., 2015) reports.

Only a persistent effort from all coastal players will allow to establish a political, legal and scientific consistent praxis that will provide tools to coastal managers to develop strategies to adapt to climate change. This will obviously pass through a clear redefinition of the framing legal network. In our opinion, even more than the dysfunctional features pointed out by Schmidt et al., (2013), there is a need to unfailingly apply the coastal adaptation programmes and ensure its reliable application. Any successful coastal adaptation is dependent on the unswerving application of its policies without allowing exceptional circumstances to deviate from its goal. If legal framework, contrary to field base solutions, is tailored for very specific narrow-minded solutions, the application of a national wide coastal adaptation programme will be undermined.

A continuous effort by all players on coastal management is essential to ensure the long-term sustainability and resilience of Portugal's coastal regions in the face of climate change. Broadly speaking, the planning framework of the coastal strip is characterised by a fragmentation between national, regional and local competences and implementation tools. The Portuguese legislative coastal programme (POC), which resulted from this call, divides the coast into six macro homogeneous zones, each covering a strip along the coast with a width of 500 m in the terrestrial area, but going up to 1000 m when justified by the need to protect coastal biophysical systems, and a maritime strip extending until the 30 m bathymetric, including areas under port jurisdiction (Dal Cin et al., 2020). The six macro zones were selected from a historic classification, and on them hinge both the current assessment and the prevention strategies. Broadly speaking, a wider spatial scope must also be adopted through precautionary regulation (jurisdictive framework) that, articulated with Local and Regional Coastal Management (POC's) will provide the legislative base for a responsible use and development of Portuguese coastal areas.

Here, based on the work by Bongarts Lebbe et al. (2021), we proposed the following conceptual framework for coastal governance (Figure 3.3.51). In our perspective, implementing soft protections and designing new integrated coastal models is the most reliable coastal adaptation approach.

Figure 3.3.51 – Conceptual framework for coastal governance based in Bongarts Lebbe et al. (2021).

Within the scope of the National Roadmap for Adaptation to climate change XXI, a trans-sectorial meeting took place on the 4th of May 2023 and, among other aspects, also reflected on the challenges faced by Portuguese coastal managers regarding the adaptation to climate change. After the discussion, and considering the results from both the dynamic high-resolution modelling across each of the five key-locations, as well as the large-scale parametric modelling for all Portuguese coastal areas (the reader is referred to the WP4.5/6 sectorial modelling report, as well as to Lemos et al. (2024a; 2024b) a group of eleven strategies was defined as the most suitable to be applied within the Portuguese coastal context. These are detailed below, with the inclusion of relevant examples and direct association to the results of the WP4.5/6.

3.3.2.1. Artificial beach nourishment

According to APA's internal database (data updated from Pinto et al. (2020), beach nourishment projects conducted along mainland Portugal totalized 199 interventions until November 2023. Of all the recorded interventions, 67% were performed on the west coast, and 33% were carried out along the south coast. Considering each section's total extension of shoreline, the southern coast has a higher nourishment density:

0.25 fills/km comparing to 0.11 fills/km on the west coast. On the west coast the interventions are concentrated in the northern and central regions, most of them associated with the main inlets and harbors (e.g., Leixões harbor, Ria de Aveiro, and Mondego and Tagus rivers inlets). Note, nevertheless, that the highest erosional trends were found for the Portuguese northern and central regions (Lira et al., 2016), and that the trends are projected to remain relatively stable (although with a slight expected magnitude decrease) towards the end of the 21st century, for both the RCP4.5 and RCP8.5 scenarios (WP4.5/6 report and Lemos et al., 2024a; 2024b). On the south coast, beach nourishments are conducted essentially along the rocky and soft cliff coastlines (in western Algarve), and along Ria Formosa barrier island system (Pinto et al., 2020).

The sum of volumes deposited between 1950 and November 2023 amounts to 46.5 x 10^6 m^3 (APA's internal database, updated from Pinto et al., 2020), with interventions ranging from tens of thousands (*e.g.*, pocket beaches near Cascais and the western rocky coast of Algarve) to more than one million cubic meters (*e.g.*, low-lying sandy coastal section south of the Aveiro inlet). Small magnitude fills (with volumes between 0.05 x 10^6 m^3 and 0.1 x 10^6 m^3) are predominant and represent 50% of all interventions. Medium magnitude nourishments (between 0.1 x 10^6 m^3 and 0.5 x 10^6 m^3) represent 36% of all interventions, medium to high magnitude nourishments (between 0.5 x 10^6 m^3 and 1 x 10^6 m^3) amount to 7%, and high magnitude interventions (volumes above 1 x 10^6 m^3) represent 7% (APA's internal database, updated from Pinto et al., 2020). Nourishment operations carried out in the south coast are typically less than 1 x 10^6 m^3 and a total of 11.4 x 10^6 m^3 have been deposited since 1970. On the west coast, 35 x 10^6 m^3 have been deposited since 1950, with more than half (22.5 x 10^6 m^3) in Costa Nova and Costa da Caparica regions, down drift of major inlets – Aveiro and Tagus (Lisbon), respectively.

In the WP4.5/6 report, it was shown through dynamic modelling that along the five key-locations (which include the most nourished areas during the last 70 years), the current erosional trends are projected to slightly decrease in the future, compatible with the overall projected changes in nearshore wave energy. This slight alleviation of the currently observed erosional trends was shown to range between 0.04% and 6.33%. Nevertheless, such changes were deemed non-statistically significant, as the ensemble uncertainty ranges were shown to be of greater magnitude than the projected changes. Therefore, this adaptation measure should be considered in the context of an extension of current beach nourishment needs towards the end of the 21st century, along the entirety of the Portuguese coastlines.

3.3.2.2. Definition of safeguard zones and relocation

Practice of coastal zone management in Portugal started in the early 1990s with the Decree-Law nº 309/93, that regulated the drafting and approval of the first Portuguese Shoreline Management Plans (*i.e.*, *Planos* *de Ordenamento da Orla Costeira* - POOC, in Portuguese). Between 1998 and 2005, the POOC were developed for nine sectors of the mainland Portuguese coast, providing a full analysis of coastal systems and a delimitation of uses in relation to the carrying capacity of the shoreline. The spatial range of this regulation framework increased steadily throughout the years. Its basic concept is to provide rules and regulations, as well as good practices, in coastal management. The Portuguese territorial management system was organised into three distinct levels (national, regional and municipal) being adjusted in 2007 with the simplification of plan's approvals and the addition to the *Planos Especiais de Ordenamento do Território* (PEOTs) special plan for estuaries, the *Plano de Ordenamento dos Estuários* (POE; Decree-Law nº 54/2007). In 2014, Decree-Law nº 31/2014 cancelled the previous legislation, putting in place a new law on general grounds of the *Lei de Bases Gerais da Política Pública de Solos, de Ordenamento do Território e de Urbanismo* (LBPPSOTU; Oliveira et al., 2020). This new basic law relies on an inclusion of environmental policies on spatial and urban planning, an incentive for inter-municipal cooperation and the intention to simplify and streamline the operation of the system planning. The approach to planning via Territorial Management Tools (IGTs) is divided into four areas (national, regional, inter-municipal and municipal) and is indicated as IGT plans and planning programmes (Oliveira et al., 2020). After the initial coastal management plans (POOC), with a life duration of approximately 10 years, new plans were established for Mainland Portugal. Following European and national (Decree-Law nº 80/2015 and Decree-Law nº 159/2012) policies, the regulation for the new *Programas da Orla Costeira* (POC) was created. The new POC correspond to updated versions of the POOC in light of the changes in the territorial management system through the LBPPSOTU. These plans began implementation in 2017, defining specific coastline activities, regulating the beach use, protection and conservation of nature, the socio-economic development, efficient use of space and protection of the environment and natural resources, and establishing the defence and promotion of historical and cultural heritage. The main goals are:

1) Defining safeguard regimes;

2) Protection and management by establishing preferred uses;

3) Conditional and prohibited uses in the intervention area:

4) Articulation and harmonisation of intervention schemes and measures contained in other IGT and planning instruments of coastal and inland marine waters (Article paragraph 3, point 1, Portuguese Decree-Law nº 309/93).

The revision of the POOCs was deemed necessary due to their evaluation in 2006 by the Ministry of Environment, Spatial Planning and Regional Development, that determined the need to review the provisions of these land management instruments, to upgrade plan proposals, to deal with the unequal treatment of land and sea tracks protection, lapses, inaccuracies and cartographic disabilities, inflexibility of beach plans and non-execution of the operating units of planning and management (Oliveira et al., 2020). Each of the new POC covers a strip along the coast, which is known as land protection zone, which is 500 m wide onshore and can extend to 1000 m when justified by the need to protect coastal biophysical systems, and a maritime range up to 30 m of water depth, with the exception of areas under port jurisdiction.

The success of the POOC/POC is unquestionable for the Portuguese coastal systems and its sustainable development. The implementation of POOC/POC was responsible for a more responsible use of the coastal area and a more thoughtful planning for these areas. Nevertheless, the dynamic social and physical aspects connected with the coastal zone imply a constant effort to mitigate and adapt to new challenges.

Considering the results obtained in the context of the Coastal Vulnerability Index (CVI), developed for the entire Mainland Portugal coastlines, and expressed in the WP4.5/6 report, it is recommended that the next generation of POC (to be established within the next decade) should adopt a probabilistic approach on the definition of safeguard (protection) zones, moving away from fixed thresholds, as the current 500 m (or 1000 m) wide stretches. The raw CVI cartography, produced within the context of this project, may become a useful tool to update the protection zones in the new generation of POC.

3.3.2.3. Rehabilitation of dunes and use of nature-based solutions

Dune rehabilitation (also referred to as “dune restoration”) is a pivotal tool to decrease coastal erosion trends or, at least, to mitigate its effects. Roughness variations (increases) may provide a buffer to the impacts of rising water levels. Several areas along the Portuguese coast have applied this strategic adaptation approach. A successful case was project ReDuna developed along the shoreline of Almada council (south of the Tagus estuary). In Praia de São João da Caparica, new dunes were created and vegetated in front of the existing dune system, palisades were raised, and dune morphological and textural changes were monitored for several years (Pais et al., 2022). This proof-of-concept project provided useful insights into the increase in dune height and extension along the years and tested robustness of coastal defences to extreme events that occurred during the monitoring period.

This project provides a clear example of dune rehabilitation and its benefits along the Portuguese coastlines. The ReDuna project started in 2014, in response to the impacts of strong winter storms in the Costa de Caparica coastline, which caused the destruction of the dune system, especially in Praia de São João da Caparica. After this event, the beach was artificially nourished and the dune profile along 1 km of coast was restored using willow sand fences. Furthermore, native dune plant species were planted to help the recovery process. For this end, seeds were collected from a close area to preserve the local genetic integrity of the site. Additionally, human pressure mitigation measures were implemented, such as pathways, fences and public project communication sites. The construction phase spanned for 6 months. The ReDuna project established strong community involvement from the very beginning. The area's design was presented, discussed and defined with engagement of target groups, who could identify themselves with the project goals and actions from an early stage. After the implementation phase, several maintenance actions followed, which included native species plantation and invasive alien species removal with the involvement of the local community, governmental organizations and schools, with the support of the Municipality's Environmental Education and Awareness Division (https://networknature.eu/casestudy/22495).

Geomorphological and ecological parameters were monitored at six-monthly intervals initially, and then yearly, with indicators as geomorphological evolution, beach-dune sediment stock, biodiversity colonization (new plants and animals), vegetation survival, community structure evolution, impact of fences on survival, growing and establishment of plants, for example. To detect the site's geomorphological changes, a GPS-based monitoring of the transect was performed, creating a 3D-model of the dunes. Nowadays, photographic data can be easily obtained by drones, which is a non-intrusive method. Owing to the photographic data collected, the survival and growth rate of the dune vegetation as well as the colonisation of new plants in the dune system was (and can still be) analysed (https://networknature.eu/casestudy/22495).

The results obtained during the first two years of the project showed that 90% of the planted native species survived, attracting 49 new wildlife species, which increased biodiversity and provided ecological resilience to the restored ecosystem. Four years after the initial plantation, roots were more than 4 m deep and in high density, forming a strong root network that stabilized the foredune. The restored dune fostered resilience to storm effects and coastal erosion due to a more stable sediment transfer and balance between the dunes, the beach and the ocean floor. In March 2018, the restored dunes provided an effective response to Storm Emma (https://networknature.eu/casestudy/22495). The example of ReDuna can be amplified and has been incorporated in many coastal management options along the Portuguese coast.

The impacts of long-term wave action and SLR in the sedimentary balance of the five key-locations along the Portuguese coastline were assessed using high-resolution numerical modelling to investigate the future projected shoreline evolution and their impacts in the 3-dimensional topography of the area, using the Parametric Coastal Retreat (PCR) algorithm (the user is referred to the WP4.5/6 modelling report, and to Lemos et al., 2024b). This assessment was conducted assuming no adaptive action until the end of the 21st century. It was shown that for most of the dune systems along the considered five key-locations, que long-term erosional trends were responsible for reducing the topographic heights of the dunes, breaking the dune cords, or even completely disrupting the dune system. One of the locations showing the most severe effects towards the end of the 21st century is, precisely, Praia de São João da Caparica. Within this context, the continuous implementation of dune rehabilitation measures as the ReDuna project (or similar) is paramount, especially in sandy coastal stretches with dune systems that provide natural protection to populated areas.

3.3.2.4. Cliffs stabilization

Slope mass movements on steep rocky sea cliffs are instantaneous phenomena with virtually no warning. According to Marques and Andrade (2009), understanding the evolution of cliffs is intrinsically complex, given the nature of the processes and their spatiotemporal discontinuities, which inhibits direct measurements and offers a challenge in the acquisition of continuous observational series of representative and rigorous data. Therefore, prevention, risk mitigation and direct protection are the measures of choice to sustainably deal with the evolution of the rocky coastlines.

The first step in the implementation of prevention is the knowledge and definition of the areas susceptible to be potentially affected by a mass movement, *i.e.*, the spatially definition of hazard areas. Hazard areas, limited by hazard lines, correspond to areas parallel to the shoreline where, in a pre-defined period, it is likely that effects of slope mass movements will be felt (Teixeira, 2014). For example, on the rocky coast of southwestern Mainland Portugal, where sea cliffs are sub-vertical with height varying from 5 m to 40 m, the duration of the slope mass movements lies in a narrow time window of 1–2 s. The instantaneous nature of the phenomenon precludes any action to minimize the damage after the onset of the collapse process. On steep sub-vertical rocky sea cliffs prone to slope mass movements, the actions to minimize risk and damages are therefore exclusively based on prevention (Teixeira, 2014). The same author stated that in this region over the last three decades, there has been record of several accidents caused by the collapse of sea cliffs cut on Miocene rocks. The most impacting in terms of loss of human lives occurred in the Maria Luisa beach (western Algarve). In that area, between July 1995 and June 2014, 244 slope mass movements on sea cliffs have been recorded and measured, spatially dispersed along the sea cliff front. Rock fall is the dominant movement (61%), whereas topples (21%) and karst collapse (16%) have approximately the same relevance. Block fall is the less frequent mass movement type (3%). During the analyzed period, five stacks collapsed, and two new ones were formed (Teixeira, 2014). The field inventory compiled by Teixeira (2014) showed an average frequency of 13 movements/year with a range of 2–42 annual movements.

Note that, nevertheless, rocky cliffs are identified in approximately 50% of the Portuguese coastline. Between 1995 and 2022, a total of 1774 slope mass movements were identified, from which 37 were in the Centro region, 1093 in the Lisbon region, 160 in Alentejo and 484 in Algarve (APA Internal Database).

Some of these have directly impacted human lives, resulting in 19 injured people and 9 fatalities (Figure 3.3.52).

Nome	Concelho	Data	Feridos	Mortos
Praia da Maré das Porcas	Albufeira	22 de março de 1998	0	1
Praia do INATEL	Albufeira	7 de novembro de 2000	3	0
Praia da Almagreira	Peniche	4 de agosto de 2005	0	2
Praia do Magoito	Sintra	23 de julho de 2006	1	0
Praia Maria Luísa	Albufeira	21 de agosto de 2009	3	5
Praia do Vau	Portimão	26 de maio de 2010	1	0
Praia dos Beijinhos	Lagoa	11 de novembro de 2010	1	0
Praia de São Bernardino	Peniche	15 de agosto de 2011	6	0
Cabo da Roca	Sintra	26 de novembro de 2012	1	0
Praia da Ursa	Sintra	15 de março de 2018	1	1
Praia de Nossa Senhora	Odemira	26 de agosto de 2018	2	0
		Total	**19**	**9**

Figure 3.3.52 – Injuries and fatalities resulting from mass movements along the Portuguese coastline, between 1995 and 2022 (APA Internal Database).

Therefore, strategies to mitigate cliffs' instabilities are usually applied, divided, according to APA, in three different categories: soft interventions, related to the controlled removal of unstable blocks or surface geodrainage; intermediate interventions, including slope netting (hexagonal meshes or tensile networks), reprofiling, vegetation and/or geosynthetic reinforcement; hard interventions, encompassing shotcrete lining, support walls, nailing techniques, and earth-retaining structures.

In the WP4.5/6 report, the CVI was compiled for the entire Portuguese coastline, including rocky areas and pocket beaches surrounded by cliffs. One of the main conclusions of this assessment is that the continued rising sea levels and wave action should contribute to shoreline retreat along most of Mainland Portugal's coastline. Even considering other adaptation strategies to mitigate these impacts, such as beach nourishment and dune rehabilitation, in specific locations, especially in the southwestern coastal areas (southern Alentejo and western Algarve), many small beaches may temporarily disappear (Taborda and Ribeiro, 2015), exposing the base of the rocky cliffs to wave action. In these locations, especially if human occupation is frequent, cliff stabilization is suggested.

3.3.2.5. Maintenance and construction of groins, breakwaters, barriers and dykes

In order to counteract an erosive tendency, between the 1950s and early 1990s, groin fields and seawalls/revetments were built in order to stabilize the shoreline and, tentatively, increase the beach width along the Portuguese coast (Sancho et al., 2023). Overall, as of 2023, there are 76 groins, 40 breakwaters (including harbor and detached structures) and 25 seawalls (barriers) along the Portuguese coastline. The policy option to “hold the line” is often applied when seaside resorts or other recreational facilities are at risk. Especially in the southern European countries France, Spain and Portugal, but also often in the southern part of the United Kingdom and Ireland, tourism plays a leading role at the protected sites. This approach has, nevertheless, become less explored, and present along mainland Portugal. Nevertheless, in some areas where the erosion stress is menacing the life of humans or disrupting economic activities, this hard-line strategy is still applied. Areas such as Ofir, Esmoriz-Cortegaça, Furadouro, Cova Gala and Costa de Caparica, groins and breakwaters were built along the coast, to mitigate erosional impacts. In the vicinity of several harbors (*e.g.*, Leixões, Figueira da Foz, Sines), breakwaters were (and continue to be) built to increase safety and operability conditions in the respective bar channels.

One case study was presented by Maia et al. (2015), in the sector between Vagueira and Labrego beaches, where the behaviour of the shoreline in the last 52 years was analyzed, and the cost-benefits and impacts of coastal protection options (including groins, seawalls and also designated revetments) was evaluated at local level. Sandy dykes are present at the south of the Vagueira and Labrego groins; downdrift, the groin and dyke have been reconstructed and reinforced several times, as a result of critical erosion during winter storms. The last major reconstruction work took place in 2011, following episodes of overwashing and the opening of a temporary tidal channel. In February 2014, the sandy dyke was reinforced after severe storms (Maia et al., 2015). In this area, between 1958 and 2010, the shoreline showed an average retreat of -3.5 m/year, which reflects the erosional trends of most of the north and central littoral sectors. Before the construction of coastal defences, a mean value of -3.2 m/year had been recorded, reverting up to +2.5 m/year after the intervention (Maia et al., 2015). The decrease in the shoreline retreat rates was not verified north or south of the Vagueira stretch due to the coastline fixation in the urban front (Maia et al., 2015). Although the retreat has diminished in relative terms, there was an increase of erosion downdrift (southward) of the groins, leading to the partial destruction of the frontal dune system, and their reinforcement (or, locally, total replacement) by sandy dykes. Maia et al. (2015) demonstrated that the coastline retreats in the Vagueira waterfront and updrift of the Labrego groin would be greater without defence structures, while in areas protected by groins, the retreat would be less significant in the absence of the protective structures. This is an example that can be extrapolated for similar specific coastal contexts, namely those where urban density is high and there is a lack of accommodation space for natural base solution to perform with success.

To face this conundrum, Lima et al. (2020) proposed a new innovative approach integrating a cost-benefit methodology and software application to analyze the impact of coastal defence interventions. The integrated methodology consists of: shoreline evolution in a medium-term perspective; coastal structures pre-design; and finally, the cost-benefit assessment (Lima et al., 2020). The performance of groins can be analyzed by assessing the effectiveness of different scenarios, from a physical and economic point of view, leading to an integrated global assessment of coastal defence interventions, enhancing the capability of finding the best physical and economical solutions (Lima et al., 2020).

Most of the hard defence structures that are still present today in the most vulnerable locations along Mainland Portugal's coastline were built in the second half of the 20th century (e.g., Figure 12 of Pinto et al., 2020). A definitive balance between the vantages and disadvantages of groins and breakwaters in local sediment dynamics is hard to obtain, and some interventions, while necessary to protect specific sites such as urban fronts, led to significant negative impacts downdrift. While it is hard to predict the local needs concerning the construction of new groins and breakwaters along the Portuguese coastline (as it requires very local-specific studies), it is generally agreed that the current existing structures should (with some exceptions) remain erected during the next decades, at least. Nevertheless, considering the future extreme coastal flooding projections presented for the five key-locations along the Portuguese coastline, in the WP4.5/6 modelling report, the inclusion of additional levels of protection along the currently existing hard defence structures, as well as their longitudinal extension (for example, considering the seawall at Costa da Caparica), is suggested. In fact, the results from local dynamic modelling (considering both scenarios, until 2100) revealed maximum topographic heights of 9.58 m, 8.82 m, 7.16 m, 8.09 m and 7.50 m for the runup lines associated with the extreme coastal flooding projections at Ofir, Costa Nova, Cova Gala, Costa da Caparica and Praia de Faro, respectively. These values, obtained from a 6-member ensemble, are accompanied by inter-member uncertainties, that when integrated for all future periods and scenarios, amount to 2.12 m, 1.28 m, 0.89 m, 0.81 m and 0.54 m, respectively. Therefore, in an attempt to consolidate all the results presented in the WP4.5/6 report into objective reference values regarding the required heights for the coastal protection structures to withstand the future projected extreme coastal events (including a measure of uncertainty, also useful to deal with the statistical possibility of severer events), the maximum topographic heights found for each key-location should consider an additional level of protection, in this instance, corresponding to half of the local uncertainty range. Therefore, the final integrated topographic heights that hard defence structures in each key-location should be accommodated to (or built towards) are set at 10.64 m, 9.46 m, 7.61 m, 8.50 m and 7.77 m, respectively (relative to the National Vertical Datum CASCAIS1938).

3.3.2.6. *New measures proposed by the stakeholders during the trans-sectorial workshop (WP1)*

In the framework of the RNA2100 project, a workshop with end-users and stakeholders occurred and some new measures were suggested:

1) Revision of legislation related to IGTs, along with its enforcement to safeguard the infrastructure, communities, and ecosystems in coastal areas;
2) Accommodation of urban coastal areas and harbor infrastructure;
3) Relocation/removal of structures exposed to risk;
4) Incremental and adjustable implementation of a variety of adaptation measures (*i.e.*, from accommodation to relocation);
5) Declaration of the Portuguese littoral as a climate emergency zone.

3.3.3. Site-specific adaptation solutions

Mainland Portugal's coastline extends for approximately 990 km, comprising long linear beach-dune systems, cliffs associated to rocky platforms and pocket beaches, estuaries, coastal lagoons and barrier islands. Beach sediments range from fine to coarse materials, mostly sand, and to a lesser extent, gravel (Pinto et al., 2020). The coast is high-mesotidal, with asymmetric wave climate owing to the different exposure to the North Atlantic, namely a high-energy wave regime in the west coast and milder conditions in the south coast. Approximately 30% of the coastline has been altered by urban settling, harbour and industrial facilities, and tourism infrastructures, accommodating approximately 75% of the population (Andrade and Freitas, 2002). In Portugal, the coastal area (up to 50 m inland) belongs to the State, and any private parcel within this domain has a public and administrative easement, according to Decree-Law nº 54/2005, modified by Decree-Law nº 78/2013 and Decree-Law nº 34/2014. Therefore, its management and protection policies are a responsibility of State coastal authorities (Fidélis and Antunes, 2014).

An assessment of coastal evolution over the last 50 years has been performed by Lira et al. (2016). The most under threat beach erosion issues were observed on the coastal stretches of Espinho–Torreira, Costa Nova–Praia de Mira, Cova da Gala–Leirosa and Cova do Vapor–Costa da Caparica (Figure 3.3.53). Reasons for this behaviour rely on the intensity and extent of the erosional behaviour exhibit major human interventions, many of which originated and maintained a sediment deficit (Lira et al., 2016). This project analysed projections for 5 very vulnerable areas that partly coincides with the ones identified by Lira et al. (2016).

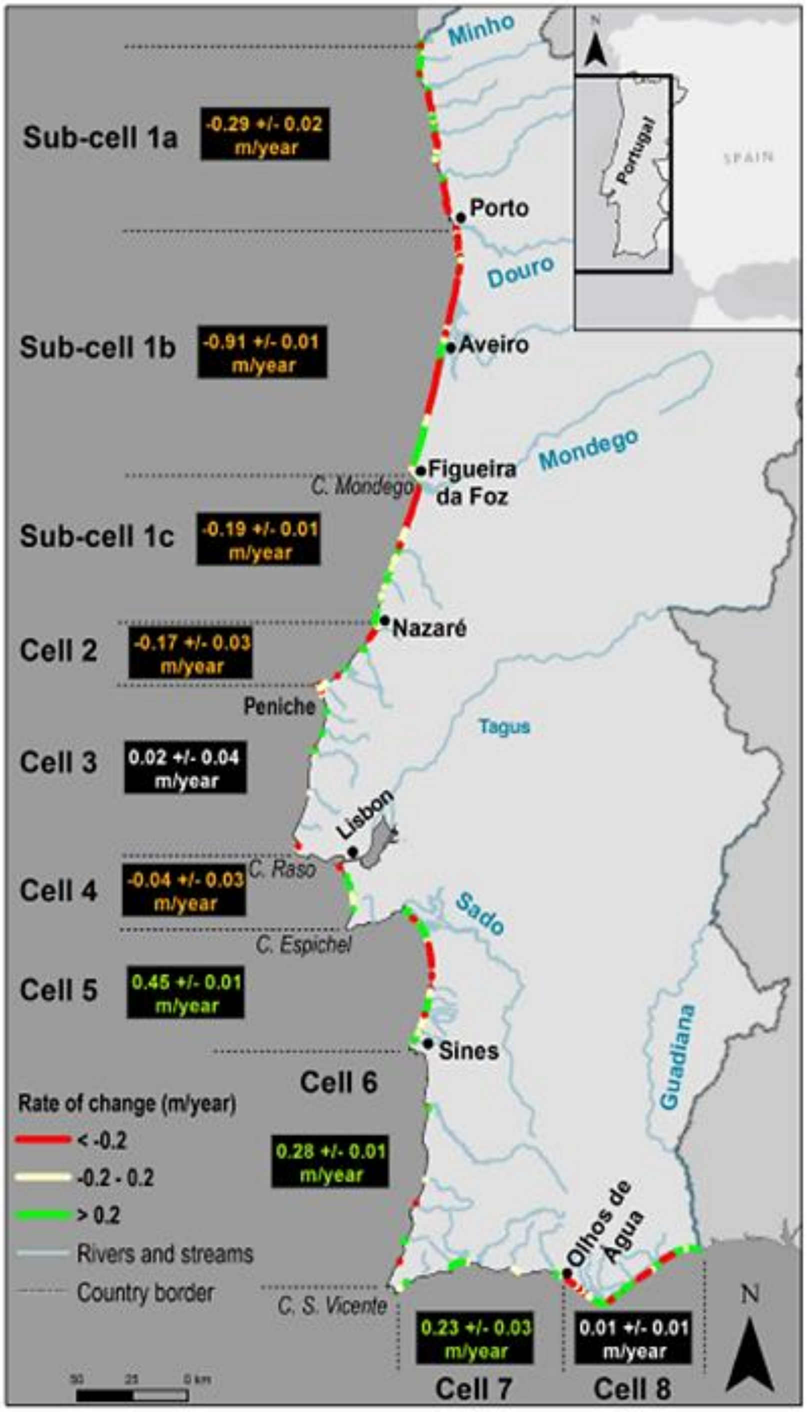


Figure 3.3.53 – Coastal morphodynamic cells along the Portuguese coast and rates of change (Lira et al., 2016).

The possible solutions to adapt the five-under-threat coastal key-locations (Ofir, Costa Nova, Cova Gala, Costa de Caparica and Praia de Faro – for which dynamical modelling was conducted in WPs 4.5 and 4.6) to the likely climate change scenarios anticipated until the end of the century are shown in Table 3.3.7, classified based on their usefulness along each coastal stretch. Here, focus is on sandy coastlines, which are highly dynamic in time and space, and constitute a substantial part of the world's (Luijendijk et al., 2018) and the Portuguese coastal areas (42%, or approximately 414 km, according to Pinto et al., 2020). Other morphological settings will require different specific solutions. Naturally, coastal environments dominated by cliffs exhibit different land occupations, and their erosional endurance is more dependent on lithological characteristics which narrow down the available adaptation solutions.

Table 3.3.7 – Possible adaptation strategies presented by study area. Scale: 0 - Not applicable; 1 - Relevant; 2 - Important; 3 - Crucial. Underlines values correspond to measures that are currently being applied.

Coastal adaptation strategy	Ofir	Costa Nova	Cova Gala	Costa da Caparica	Praia de Faro
Maintenance and construction of groins, breakwaters, barriers and dykes (2 measures)	<u>2</u>	<u>2</u>	<u>2</u>	<u>2</u>	0
Cliff stabilization	0	0	0	0	0
Rehabilitation of dunes and use of nature-based solutions	3	2	2	<u>3</u>	3
Definition of safeguard zones and relocation	1	1	1	1	1
Artificial Beach Nourishment	<u>3</u>	<u>3</u>	<u>3</u>	<u>3</u>	<u>1</u>
Revision of legislation related to IGTs, along with its enforcement to safeguard the infrastructure, communities, and ecosystems in coastal areas	2	2	2	2	2
Accommodation of urban coastal areas and harbor infrastructure	2	2	2	1	1
Relocation/removal of structures exposed to risk (long-term measure)	2	2	2	1	3
Incremental and adjustable implementation of a variety of adaptation measures (*i.e.*, from accommodation to relocation)	1	1	1	1	1
Declaration of the Portuguese littoral as a climate emergency zone	1	1	1	1	1

3.3.4. Adaptation costs

3.3.4.1. Introduction and framework

Adaptation measures often come with costs, which can hinder its effectiveness, especially from the socioeconomic point of view. As future extreme coastal events along the Portuguese coastline are projected to become more severe in the future, mostly due to the changes in total water levels induced by SLR, adaptation assumes a crucial role to defend people, goods and critical infrastructure against coastal erosion and (both episodic and permanent) flooding.

Traditionally, adaptation techniques relied heavily on civil engineering approaches (hard interventions), without the associated cost and benefit considerations. Since the 1990s, the focus moved from physical effectiveness to a more holistic perspective that entails the comprehensive management of coastal zones (Integrated Coastal Zone Management, according to the recommendation of the European Parliament and of the Council 2002/413/EC), evaluating adaptation measures with economic tools such as cost-effectiveness, cost-benefit and efficiency analyses (Breil et al., 2007). As future investments required to defend the Portuguese coastal areas are expected to increase, improved knowledge on their performance for impact mitigation, costs and benefits, is required.

When considering adaptation costs, two types of information must be included: the costs related to new interventions (such as artificial beach nourishments), and the ones arising from periodic maintenance of pre-existent structures. Occasionally, the costs related to the accommodation of such structures, to include new levels of protection, are considered. Finally, the comparison of the adaptation costs with the total inaction ("no-action"; TIC) ones allows the cost-benefit evaluation of the considered strategies. Throughout scientific literature, cost-benefit studies have been used to assess the costs (installation and maintenance), benefits (avoided costs) and net benefits (benefits minus costs) of individual and combinations of adaptation measures (e.g., Turner et al., 2007; Roebeling et al., 2011; Alexandrakis et al., 2015; Martino and Amos, 2015; Coelho et al., 2016).

The combination of the adaptation strategies with the dynamic modelling results from the WP4.5/6 report allows the determination of the best approach in terms of efficiency, through the identification of an optimal strategy (i.e., that provide the largest net benefits; e.g. Darwin and Tol, 2001; Bosello et al., 2007; Costa et al., 2009; Neumann et al., 2015). Such an analysis allows the translation of numerical modelling efforts into adaptation policies and socioeconomic impacts, effectively contributing to the definition of coastal zone protection strategies. Examples in scientific literature include Smith et al. (2009) and Landry (2011), which assessed the frequency and amount of sediments necessary to achieve an optimum artificial beach nourishment, and Tsvetanov and Shah (2013), which analyzed the optimal timing of investment considering a pre-defined increase in the height of seawalls/levees.

3.3.4.2. Methodology

Here, the adaptation costs and benefits for the coastal areas of Mainland Portugal are analyzed, considering a large database of historical interventions of various natures, from artificial beach nourishments to cliff stabilizations, including adherent structures, groins and breakwaters. The original construction costs are identified (according to the buying power of 2023, considering Portuguese historical inflation rates), and future investments and maintenance costs are projected, based on scientific literature and expert knowledge from APA technicians (also considering 2023 values). Note that, here, the adaptation costs refer to the values, in euros (€), required to achieve, towards the end of the 21st century, the same level of coastal protection as in 2023, along the Portuguese ocean-facing coastlines, considering the domains of the POCs. New interventions are only quantified when there is evidence that these will be conducted. The remainder of the adaptation costs refer to maintenance of currently existing infrastructure, and the preservation of current coastal protection levels (considering the future projected changes in the extreme run-up). These costs are then compared to the total inaction ones, in order to establish the cost-benefits at national and NUTSII scales.

The adaptation costs are calculated for six adaptation measures: artificial nourishments, groins, adherent structures (*e.g.*, seawalls), breakwaters, dykes and cliff stabilizations. Other measures, proposed in the previous section, were considered either too abstract (*e.g.*, Definition of safeguard zones and relocation; Revision of legislation related to IGTs, along with its enforcement to safeguard the infrastructure, communities, and ecosystems in coastal areas; Incremental and adjustable implementation of a variety of adaptation measures (*i.e.*, from accommodation to relocation); Declaration of the Portuguese littoral as a climate emergency zone) or simply did not dispose of enough associated economic data to be accounted for (*e.g.*, Rehabilitation of dunes and use of nature-based solutions; Relocation/removal of structures exposed to risk). The historical construction/implementation costs are also quantified, through the creation of the largest national database for economic costs related to adaptation measures (in partnership with APA), displaying accurate values since the 1950s (both original and inflation-adjusted to 2023).

Different approaches were considered for each adaptation measure, given their intrinsic physical and economic differences. Regarding artificial beach nourishment, *i.e.*, the deposition of sand or sediment in eroded beaches, such strategy has been considered in Portugal since the 1950s (Figure 3.3.54).

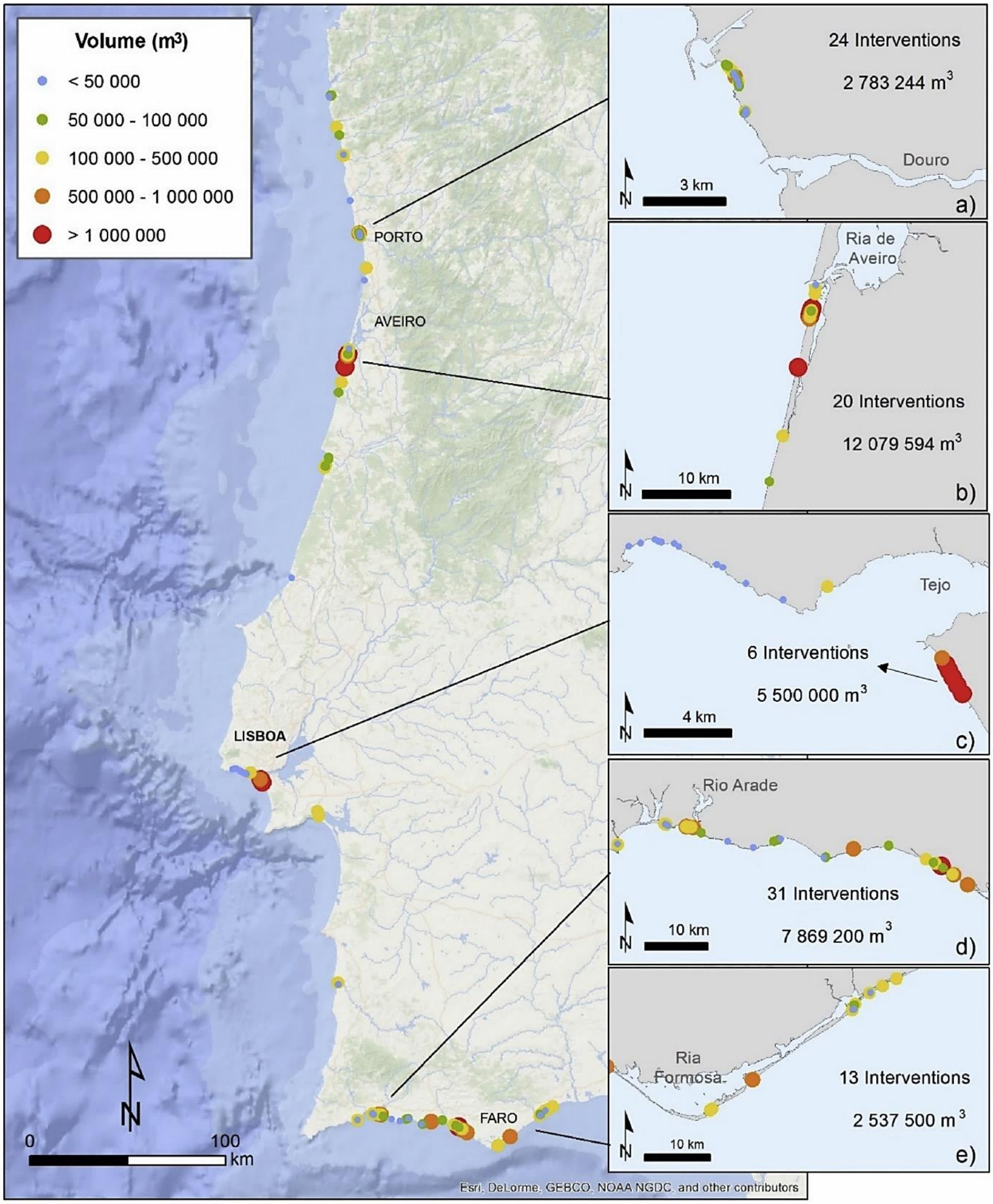


Figure 3.3.54 – Location and magnitude of beach nourishment interventions along mainland Portugal between 1950 and 2017. Boxes detail the locations of the most relevant interventions (in number and volume). From Pinto et al. (2020).

The implementation of this measure, to sustain the high erosion trends especially in central Portugal, has, nevertheless, been restricted to highly populated areas, proximity to harbours, and local availability of dredged sediments, given the high related economic costs of such interventions. Therefore, while most of the Portuguese coastlines are in fact eroding, beach nourishment has been (and will be) used when local needs arise, and not as a large-scale measure. The adaptation costs related to this measure are mainly based on the continuity of past interventions, considering, nevertheless, future planned interventions (*e.g.*, Costa Nova, Cova Gala, Caparica, Carvoeiro-Albufeira, Quarteira-Garrão). Note that for Costa Nova, a close borrow site may provide up to 28 million m^3 of sediment, being a dredging plan in place to extract up to 600 thousand m^3 per year. This is also true for the Albufeira and Quarteira regions, with up to 8 and 15 million m^3 of available sediment. All future projected interventions (both new and following past patterns) are scaled considering the future projected trends in the longshore sediment transport, identified in the WP4.5/6 report, directly resulting from dynamical modelling. These trends are slightly negative throughout the Portuguese coastlines, suggesting a reduction in present erosion trends, from 0.04% to 6.33% until 2100. The yearly normalized coefficients throughout the 21st century (based on dynamic modelling from 2011 to 2100), for the five key locations, are identified in Table 3.3.8, for each scenario.

Table 3.3.8 – Future projected longshore sediment transport normalized trends (m3/m3/year), throughout the entire 21st century (2011-2100), at each of the key-locations, considering the RCP4.5 and RCP8.5 scenarios.

Longshore sediment transport normalized trends (m^3/m^3/year)		
	RCP4.5	RCP8.5
Ofir	-0.00173	-0.000576
Costa Nova	-0.000341	-0.000897
Cova Gala	-0.00189	-0.00187
Costa da Caparica	-0.00298	-0.00531
Praia de Faro	-0.00401	-0.00795

The economic costs related to artificial nourishment interventions are distributed between real values and estimates, using expert knowledge from APA technicians. Overall, 21 interventions/sets of interventions are associated with real values, averaging at 6.16€/m^3 (not adjusted to 2023). The remaining 55 interventions identified are associated with expert knowledge values, up to 8€/m^3 (referent to 2023).

Considering groins, *i.e.*, hard structures that were built along the Portuguese coastline especially between the 1950s and the 1990s, this type of intervention has been progressively replaced by softer approaches, such as artificial beach nourishment or nature-based solutions. Nevertheless, as of 2023, there are 76 groins along the Portuguese coastline. Since new interventions regarding the construction of groins are not planned in the future, the adaptation costs related to these structures are mainly based on their maintenance towards the end of the 21st century, as well as on the accommodation efforts necessary to provide the same level of protection in the future as under present climate conditions. The information regarding the new structural heights is given by the dynamical modelling results present in the WP4.5/6 report, expressed in section 3.3.2.5. of the present document.

The quantification of the economic costs of construction related to groins are distributed between real values and estimates, using information from APA reports and values from Alves (2012) and Roebeling et al. (2018), respectively. Such estimates are expressed in Table 3.3.9, updated, nevertheless, to 2023 values. While there is no fixed reference for adaptation costs related to maintenance of groins, and references vary greatly (e.g., Lima et al., 2018; Roebeling et al., 2018), here, these amount to 30% of the construction value at every 10 years (Table 3.3.9). While this value can be considered conservative, note that some structures might be abandoned in the future.

Table 3.3.9 – Groin construction and maintenance costs (in €), per meter of structure length, based on Alves (2012).

Construction and maintenance costs for groins (as of 2023)		
Length (m)	Construction cost (€/m)	Maintenance cost (€/m/30y)
100	4875	1463
200	6094	1828
300	8126	2438
400	10969	3291
500	14625	4388

Overall, from a total of 63 groins/sets of groins considered, 3 interventions are associated with real values. The remaining 60 structures/sets of structures identified are associated to the estimated values from Table 3.3.9.

Adherent structures, such as seawalls, are included in the hard defence typology, however, their implementation can serve other purposes such as leisure and mobility ones. As of 2023, there are 25 seawalls along the Portuguese coastline. Nevertheless, here, aiming at the best possible detail, other "light" structures are also taken into consideration (*e.g.*, support walls for the EN6 – Marginal route), elevating the total number to 51. Since new interventions regarding the construction of seawalls are not planned in the future, the adaptation costs are mainly based on their maintenance and on the accommodation efforts necessary to provide the same level of protection in the future as under present climate conditions (WP4.5/6 dynamic modelling report and section 3.3.2.5. of the present document).

The quantification of economic costs of construction related to adherent structures are distributed between real values and estimates, using information from APA reports and values based on Reis (2010) and Roebeling et al. (2011), respectively. The best estimate is of 10000€/m, considering 2023 values. For "light" structures, an estimate of 5000€/m is used. The distinction between a normal and a "light" structure is done considering expert knowledge from APA technicians. Similarly to the approach for groins, adaptation costs related to maintenance of seawalls amount to 30% of the construction value at every 10 years. The approach used for seawalls is also considered for breakwaters (usually associated with harbors) but keeping the 10000€/m fixed for the estimation of construction costs.

Regarding dykes, the approach for construction costs considered Nicholls et al. (2019), which also served as reference to the PESETA IV project. For Portugal, estimates ranging between 1900000 and 5200000€/km/m were presented, considering 2019 values. After updating to 2023 values, a mean value of 4064929€/km/m is considered. Note that for the current analysis, only the structures within the POC domains are considered, and therefore, tidal dykes are excluded. As before, the adaptation costs are both related to the maintenance of the dykes and the necessary accommodation efforts for these structures to provide the same level of protection in the future as under present climate conditions.

Finally, cliff stabilization interventions were considered, distinguishing between different typologies whenever possible. As of 2023, a total of 37 interventions were analyzed, using information from APA reports. The quantification of the economic costs for such interventions considers the real values present in the APA database, except for 11 interventions, to which no costs were found to be associated. These were, nevertheless, computed based on the type of cliff stabilization procedure, considering the real values for other interventions of the same category. The mean values (as of 2023) associated with the three main types of intervention, per linear meter of length, are summarized in Table 3.3.10. Since new interventions are not possible to predict, depending on very local physical and socio-economic factors, the adaptation costs related to cliff stabilization are mainly based on their maintenance towards the end of the 21st century.

Table 3.3.10 – Cliff stabilization interventions and maintenance costs (in €), per meter of length.

Real values associated to cliff stabilization interventions and maintenance (as of 2023)		
Type of intervention	Mean value (€/m)	Maintenance cost (€/m/30y)
Nets	3870	1161
Dynamic barriers	8435	2531
Shotcrete	8398	2519

3.3.4.3. *Results*

A total of 278 interventions were considered in the adaptation measures’ database, using information and expert knowledge from APA. Note that some of the interventions correspond in fact to “sets of interventions”, when the implementation requires multiple localized efforts or the associated costs refer to more than one operation, providing that it respects the same typology. Furthermore, these correspond only to the six categories that were considered: artificial beach nourishment, groins, adherent structures, breakwaters, dykes and cliff stabilization. Therefore, the real values may be slightly underestimated.

Considering the construction costs, *i.e.*, the total nationwide economic costs related to the implementation of adaptation measures in the past (1959-2023), the associated values for each type of intervention are expressed in Table 3.3.11, upon their conversion to 2023, considering historical national inflation rates. The total adjusted investment in coastal adaptation measures since 1959 is found to be slightly above 1600 million €, for the six measures/sets of measures considered. Between these, the largest investment is related to breakwaters (including harbor structures), at 739 million €. Adherent structures (seawalls and other protection works) amount to 458 million €, with artificial beach nourishments coming in third place, at 226 million €. Most of the hard interventions (*e.g.*, construction of groins and adherent structures) considered took place until the 1990s, when the strategy shifted towards softer measures.

Table 3.3.11 – Construction/implementation costs (in M€) for each of the six types of adaptation measures considered, along the Portuguese coastlines, considering 2023 values.

Construction/implementation costs related to adaptation measures (as of 2023)	
Type of intervention	Construction/implementation cost (M€)
Artificial beach nourishment	226.5
Groins	145.7
Adherent structures	458.4
Breakwaters	739.1
Dykes	9.246
Cliff stabilization	63.41
All considered interventions (total)	1642

The economic costs related to all types of adaptation measures implemented prior do 2023 (inclusive) are displayed in Table 3.3.12, considering each POC domain. Most of the historical investment is found to be between Ovar and Marinha Grande, in the highly eroding coastlines of central Portugal, at 464 million €. Note that while 516 million € are shown to have been spent along the Alentejo coastlines (POC Espichel-Odeceixe), around 400 million € correspond to the construction of the Sines harbor, exceptionally including the current expansion costs, intervention that started in 2021 and thus is included in this assessment.

Table 3.3.12 – Construction/implementation costs (in M€) for all considered interventions along the Portuguese coastlines, divided by POC domains, considering 2023 values.

Construction/implementation costs related to adaptation measures (as of 2023)	
POC	Construction/implementation cost (M€)
Caminha – Espinho	283.4
Ovar – Marinha Grande	464.1
Alcobaça – Espichel	180.3
Espichel – Odeceixe	516.8
Odeceixe – Vilamoura	75.99
Vilamoura – Vila Real de Santo António	121.7
All POC domains (total)	1642

The future projected adaptation costs related exclusively from structural maintenance and the continuity of artificial beach nourishment interventions are shown in Table 3.3.13 and Table 3.3.14, considering both each type of intervention as well as the POC domains, as in Table 3.3.11 and Table 3.3.12. These partial adaptation costs are calculated for the end of each future time slice (2041-2070 and 2071-2100), considering the RCP4.5 and RCP8.5 scenarios, considering 2023 values. Overall, as expected, economic costs are greater towards the end of the 21st century. Nevertheless, due to a slight projected alleviation of the erosive trends under the RCP8.5 scenario, in comparison with the RCP4.5, artificial beach nourishment requirements become lower (to ensure the same degree of protection as currently), as well as the associated costs. Note, however, that artificial beach nourishment becomes one of the dominant adaptation measures, with economic costs surpassing those related to the maintenance of groins.

Table 3.3.13 – Future projected adaptation costs (in M€) for each of the six types of adaptation measures considered, until the end of the 2041-2070 and 2071-2100 periods, along the Portuguese coastlines, considering 2023 values.

Future projected costs related to adaptation measures (as of 2023)				
Type of intervention	Adaptation cost (M€) 2070 (RCP4.5)	Adaptation cost (M€) 2070 (RCP8.5)	Adaptation cost (M€) 2100 (RCP4.5)	Adaptation cost (M€) 2100 (RCP8.5)
Artificial beach nourishment	773.5	751.1	1238	1183
Groins	257.3	257.3	411.6	411.6
Adherent structures	701.9	701.9	1116	1116
Breakwaters	1105	1105	1768	1768
Dykes	13.87	13.87	22.19	22.19
Cliff stabilization	105.7	105.7	169.2	169.2
All considered interventions (total)	2957	2935	4724	4670

Along the POC domains, a similar behavior is found over time and between scenarios, due to the projected changes in artificial beach nourishment needs (to ensure the same degree of protection as currently). The Ovar-Marinha Grande and the Espichel-Odeceixe stretches show the greatest partial adaptation costs, up to 1474 and 1244 million €, respectively. Note, however, that for the Espichel-Odeceixe stretch, around 1000 million € are related to the maintenance of the Sines harbour.

Table 3.3.14 – Future projected adaptation costs (in M€) for all considered interventions along the Portuguese coastlines, until the end of the 2041-2070 and 2071-2100 periods, divided by POC domains, considering 2023 values.

Future projected costs related to adaptation measures (as of 2023)				
POC	Adaptation cost (M€) 2070 (RCP4.5)	Adaptation cost (M€) 2070 (RCP8.5)	Adaptation cost (M€) 2100 (RCP4.5)	Adaptation cost (M€) 2100 (RCP8.5)
Caminha – Espinho	476.5	478.7	755.9	761.5
Ovar – Marinha Grande	923.2	917.8	1489	1474
Alcobaça – Espichel	352.6	352.6	563.7	563.8
Espichel – Odeceixe	778.1	777.8	1245	1244
Odeceixe – Vilamoura	151.2	145.6	238.5	225.2
Vilamoura – Vila Real de Santo António	275.4	262.1	432.4	400.9
All POC domains (total)	2957	2935	4724	4670

A separate cost analysis is shown in Table 3.3.15, considering solely accommodation costs for hard structures (including adherent structures, groins and breakwaters – harbor infrastructure), along each POC domain. Accommodation costs were calculated based on the Nicholls et al. (2019) values, also considered in the PESETA IV report. These correspond to the adaptation costs (as of 2023) necessary to increase the height of the structures so that they can provide, in the future, the same level of protection as they currently do, assuming the projected changes in TWLs and extreme wave events found in the WP4.5/6 dynamic modelling report. Due to the greater number structures in northern Portugal, accommodation costs are projected to be greater there, up to 109 million € by 2100 along the Caminha-Espinho coastlines.

Table 3.3.15 – Future projected adaptation costs (in M€) for the accommodation of structures along the Portuguese coastlines, until the end of the 2041-2070 and 2071-2100 periods, divided by POC domains, considering 2023 values.

Future projected costs related to accommodation of groins, adherent structures and breakwaters (as of 2023)				
POC	Accommodation cost (M€) 2070 (RCP4.5)	Accommodation cost (M€) 2070 (RCP8.5)	Accommodation cost (M€) 2100 (RCP4.5)	Accommodation cost (M€) 2100 (RCP8.5)
Caminha – Espinho	57.83	52.91	84.90	109.5
Ovar – Marinha Grande	31.49	29.91	29.13	40.15
Alcobaça – Espichel	21.89	31.01	36.49	41.96
Espichel – Odeceixe	15.83	21.11	29.26	32.62
Odeceixe – Vilamoura	11.27	8.400	13.93	12.70
Vilamoura – Vila Real de Santo António	19.31	14.39	23.87	21.77
All POC domains (total)	157.6	157.7	217.6	258.7

Finally, the total future projected adaptation costs are compiled in Table 3.3.16, considering the continuity of artificial nourishment interventions, the maintenance of currently existing structures as well as the necessary adjustments in structural heights in order to provide the same level of protection as today. The total adaptation costs are divided, geographically, into the POC domains, districts and NUTSII regions. At national scale, slight differences are visible in the total values aggregated considering different geographic units due to the attribution of accommodation costs per unit.

Along the POC domains, total adaptation costs are projected to range between 162 and 954 million € by 2070 under RCP4.5, for the Odeceixe-Vilamoura and Ovar-Marinha Grande stretches, respectively. By the end of the 21st century (2100), total adaptation costs are projected to range between 252 and 1517 million € under RCP4.5, and 237 and 1514 million € under RCP8.5, in the same stretches. Although values are projected to be slightly lower under RCP8.5 in these stretches, along Caminha-Espinho and Alcobaça-Espichel, costs assume the highest for RCP8.5. These differences are related to the balance between artificial nourishment and structural accommodation needs, which are projected to act in opposite directions under RCP8.5.

Table 3.3.16 – Future projected adaptation costs (in M€) considering both the continuity of interventions and maintenance of structures, as well as structural accommodation along the Portuguese coastlines, until the end of the 2041-2070 and 2071-2100 periods, divided by POC domains, taking into account 2023 values.

Total future projected adaptation costs Interventions plus maintenance of structures plus structural accommodation (as of 2023)				
POC	Total adaptation cost (M€) 2070 (RCP4.5)	Total adaptation cost (M€) 2070 (RCP8.5)	Total adaptation cost (M€) 2100 (RCP4.5)	Total adaptation cost (M€) 2100 (RCP8.5)
Caminha – Espinho	534.3	531.6	840.8	871.0
Ovar – Marinha Grande	954.7	947.7	1518	1515
Alcobaça – Espichel	374.5	383.6	600.2	605.8
Espichel – Odeceixe	793.9	798.9	1274	1277
Odeceixe – Vilamoura	162.5	154.0	252.4	237.9
Vilamoura – Vila Real de Santo António	294.7	276.5	456.3	422.6
All POC domains (total)	3115	3092	4942	4929
District	Total adaptation cost (M€) 2070 (RCP4.5)	Total adaptation cost (M€) 2070 (RCP8.5)	Total adaptation cost (M€) 2100 (RCP4.5)	Total adaptation cost (M€) 2100 (RCP8.5)
Viana do Castelo	82.08	82.18	130.4	134.9
Braga	40.18	39.81	63.57	66.09
Porto	325.7	324.0	516.1	535.6
Aveiro	529.4	524.5	831.6	830.6
Coimbra	491.4	489.0	782.2	781.7
Leiria	55.14	54.88	84.75	86.55
Lisboa	139.6	143.9	224.1	226.6
Setúbal	985.6	993.5	1583	1587
Beja	6.485	6.380	10.33	9.923
Faro	457.2	430.5	708.7	660.6
All ocean-facing districts (total)	3113	3089	4934	4920
NUTSII	Total adaptation cost (M€) 2070 (RCP4.5)	Total adaptation cost (M€) 2070 (RCP8.5)	Total adaptation cost (M€) 2100 (RCP4.5)	Total adaptation cost (M€) 2100 (RCP8.5)
Norte	534.3	531.6	840.8	871.0

Centro	1025	1018	1628	1626
A. M. Lisboa	372.1	381.2	596.4	601.7
Alentejo	726.4	730.1	1165	1167
Algarve	457.2	430.5	708.7	660.6
All NUTSII (total)	3115	3092	4939	4927

Overall, the total adaptation costs are expected to exceed 3000 million € by 2070 and get close to 5000 million € by 2100, along the Portuguese coastlines. Note, once again, that if new interventions and additional levels of protection are planned in the future, these projections will be aggravated.

4. Final Remarks

4.1. Hydrological Balance & Agroforestry

The water resource sector conducted a comprehensive examination encompassing the costs associated with inaction and the initiatives taken to adapt to climate change projections. The evaluation of the costs of inaction was focused on the water resources and agroforestry sector, taking into consideration variables like the average cost of water, changes in water availability, and impacts on the productivity of key crops across various river basin districts. Additionally, we pinpointed a range of adaptation measures and employed direct and/or indirect modelling techniques to evaluate their efficacy, costs, and benefits, with a specific emphasis on measures amenable to modelling. This integrated approach provides a thorough understanding of the challenges and potential solutions within the water resource and agroforestry sectors in the face of climate change.

A reduction in water yield is projected for all river basins throughout the 21st century for RCP4.5 and 8.5. Although water yield losses are larger, in volume, in RH3, 4 and 5, the cost of water in RH6 and RH8 implies that the overall losses are greater in these basins (above 1 M€ in RCP4.5 and 3 M€ in RCP8.5).

The rising temperatures across the 21st century imply changes to crop phenology, translating into losses in productivity in all scenarios. The greatest economic loss is associated with potatoes (losses above 100 M€ in RCP4.5 and RCP8.5) and Centro is the region with the largest projected losses (-180 M€ and -297 M€ in RCP4.5 and RCP8.5 respectively).

The initial adaptation measure centres on the selection of crops better suited to climate change projections, employing a strategic approach to ensure agricultural resilience and sustainability within evolving environmental conditions, such as temperature increases and the higher likelihood of extreme weather events. In assessing the advantages of this adaptive measure, the study estimated improvements in water availability and productivity by replacing corn with sunflower crops. Notably, the transition to sunflower cultivation revealed a reduced water requirement over time, coupled with higher yields than corn.

To calculate the associated costs of implementing this measure, detailed information regarding the expenses related to sunflower and corn cultivation was acquired. The divergence in these costs in regions where corn is currently cultivated was then calculated. This comprehensive analysis enabled an estimation of the costs linked to the substitution of crops, revealing the economic viability of transitioning from corn to sunflower cultivation, particularly in the context of adapting to climate change.

The second adaptation measure, which centres on improving irrigation efficiency, seeks to minimize water consumption in agriculture. As part of this initiative, an analysis of water availability outcomes was undertaken by transitioning irrigation systems to drip irrigation, especially in contexts where its applicability is evident, such as in corn and vegetable cultivation. The findings indicated that the shift from conventional irrigation systems to a more efficient drip irrigation system resulted in a reduction in water consumption by crops. This reduction can be attributed to the precise delivery of water directly to the plant roots, thereby minimizing wastage and optimizing resource utilization. To assess the economic costs of implementing this measure, information on the average cost for the implementation of the drip irrigation system was obtained. The results of this analysis emphasised the viability and cost-effectiveness of replacing irrigation systems, particularly in terms of reducing water consumption.

The third measure implemented in this study involved reducing system water loss and leakages. The SWAT+ model does not account for water losses and leaks in the water supply system. To address this, WEI+ was recalculated considering the irrigation component obtained from modelling simulations and the information from the efficiency of the Hydro-agricultural developments. Notably, the results indicated an increase in the water stress index upon the implementation of these losses. This underscores the significance of reducing losses as essential for enhancing water availability over time.

The final measure involves water recycling and reuse, promoting a more sustainable approach to water management across various purposes. In quantifying the advantages of water recycling and reuse, the analysis took into account the results obtained from modelling simulations and a percentage of the municipal water supply. As expected, findings reflected an important augmentation in water availability in the respective regions.

Finally, additional adaptation measures were explored through workshops and interactions with influential institutions in agroforestry and water resources. These measures encompass a diverse range of strategies to address the challenges of climate change. Some of these include soil moisture conservation techniques, rainwater harvesting for storage, public water conservation campaigns, awareness and training of farmers, progressive pricing, seawater desalination, water retention landscapes, water metering and water entitlements. This comprehensive set of possibilities reflects a holistic approach to adaptation, acknowledging the multifaceted nature of challenges in the context of climate change.

4.2. Forest fires

The Fire Weather Index (FWI), widely used to assess fire danger, indicates an expected increase in western Mediterranean meteorological fire danger due to climate change. Studies focused on Portugal and the broader region consistently point to rising temperatures, fewer spring and summer precipitations, and increased extreme weather events. This sets the stage for larger, more energetic, and destructive wildfires. Results project a notable increase in FWI probability across greenhouse gas scenarios, especially under the extreme RCP 8.5 scenario, indicating a higher likelihood of more intense wildfires. The probability of megafires with energy exceeding 3000 MW is expected to double by the mid-21st century under RCP 2.6, with reductions afterward. RCP 4.5 shows a gradual increase in radiative forcing until 2060, followed by stabilisation, while RCP 8.5 exhibits a continuous rise. These findings call for urgent and effective fire prevention strategies aiming to attenuate the potential impact of climate change on wildfire occurrences. Even with ambitious efforts to reduce emissions (RCP 2.6), the risk of encountering highly energetic wildfires remains a significant concern. The continuous increase in FRP probabilities under more severe emission scenarios (RCP 4.5 and RCP 8.5) highlights the pressing need for comprehensive and adaptive wildfire management strategies to safeguard communities and ecosystems in the face of escalating fire risks. We considered three adaptation strategies of fire prevention and analysed their impacts on fire behaviour.

Strategy 1, involving a random reduction of 50% of FRPs when FWI exceeds the sample median, showcased appreciable reductions in the probability of exceedance of log10(FRP) across all energy thresholds. Notably, fires with an energy release of 100 MW showed a decrease of about 10%, whereas those with 1000 MW and very high log10(FRP) revealed reductions of about 25% and 40%, respectively. This strategy showed to be promising to curb fire occurrences in moderate fire weather conditions, however it does not deal very effectively with the most intense fires. Moreover, this strategy implies that some type of warning system and implementation strategy must be applied to a rather large number of days and regions with moderate fire danger, with high costs at the level of both resources and manpower.

In the case of Strategy 2, where 50%, 90%, and 95% of log10(FRP) were randomly reduced for FWI ranging between the 75th and 90th sample percentiles, 90th and 95th sample percentiles, and above 95th sample percentile, respectively, the impact was more pronounced than in Strategy 1. The probability of exceedance decreased by approximately 15%, 40%, and 70% for 100 MW, 1000 MW, and very large FRP, respectively. This strategy's targeted approach exhibited the potential to significantly decrease the occurrence of fires in regions experiencing extreme fire weather conditions.

Finally, Strategy 3 involved the random reduction of 95% of FRPs when FWI exceeded the 95th sample percentile. Although showing smaller reductions when compared to Strategy 2, with decreases of around 0%, 20%, and 50% for 100 MW, 1000 MW, and maximum FRP, Strategy 3 proved effective in reducing the occurrence of extremely intense fires during the most critical fire weather conditions and may lead to less but more focused resources.

It may be noted that the impacts of strategy 2 are higher than those of the other two, both for historical and future scenarios. However, this strategy is clearly more difficult to implement due to the different levels of reduction, which would need a rather complex infrastructure of warning systems and resources applied to a larger number of areas and days. Strategy 3 is therefore the one that seems more promising because it addresses the increasing challenges posed by extreme fire weather events under climate change scenarios, while significantly reducing the number of times when these measures are implemented. In fact, its effectiveness in mitigating hotspots during extreme fire weather events makes it a valuable tool in reducing the probability of occurrence of highly intense fires in Portugal. By prioritising Strategy 3, wildfire management can adopt a proactive and adaptive approach, significantly reducing the need for stringent authoritative actions during the summer while ensuring the protection of communities and ecosystems from the escalating threat of extremely energetic fires.

This report also underscores the immediate need for proactive measures to address the intensifying threat of forest fires exacerbated by climate change. Forests, vital components of our ecosystems, face escalating risks, necessitating a concerted and timely response. The urgency lies in adopting a comprehensive approach that seamlessly integrates mitigation strategies with robust adaptation measures specifically tailored to forested environments. In the context of forest fire adaptation to climate change, it is imperative to recognize the intricate interplay of ecological factors. The report advocates for a multifaceted strategy that encompasses not only traditional fire management practices but also innovative approaches such as controlled biomass burning, reduction of fuel continuity, and enhancing vegetation resilience to fire. These adaptation measures are pivotal in promoting ecosystem health, minimising the risk of uncontrolled wildfires, and safeguarding biodiversity. Additionally, the study introduces three specific modelled adaptation strategies designed to reduce ignitions, a critical aspect of forest fire prevention. Emphasising a forward-thinking mindset, the study contends that forest fire adaptation requires a proactive stance. This includes investing in advanced early warning systems, community education initiatives, and sustainable land management practices. Forested regions, particularly those prone to wildfires, demand tailored solutions that account for the unique challenges posed by climate change-induced shifts in temperature, precipitation, and vegetation dynamics. Policymakers play a central role in steering these adaptation efforts, necessitating collaboration with local communities and stakeholders. Implementing adaptive measures requires a synergy of efforts, combining scientific insights with local knowledge and community engagement. Additionally, policies should incentivize the adoption of nature-based solutions, such as afforestation and the creation of fuel breaks, which enhance the landscape's resilience to fire. This collaborative and forward-looking approach is crucial not only for mitigating immediate risks but also for building long-term resilience. The study emphasises that by prioritising the preservation and sustainable management of forest ecosystems, society can contribute to a more resilient and sustainable future. As climate change continues to reshape environmental dynamics, the adaptive strategies, including targeted measures to reduce ignitions, serve as a blueprint for safeguarding not only forests but also the broader well-being of societies and ecosystems. Only through concerted efforts, guided by a commitment to environmental preservation, can we effectively address the complex challenges posed by climate change-induced forest fires.

4.3. Coastal areas

The continued rise in water levels along the Portuguese coastlines, resulting from future changes in the behavior of extreme storm surges and wave events in the context of SLR, is expected to result in unprecedented coastal flooding (Santos et al., 2014), exacerbated if no adaptation measures are considered. The combination of coastal retreat with episodic flooding related to extreme events reveal severe impacts on population, infrastructures and livelihood along several urbanized stretches of the Portuguese coastline. Furthermore, future extreme coastal flooding may result in loss of low-lying coastal ecosystems as well as inland fertile soil for agriculture, given the potential landward intrusion of saltwater. Although SLR plays an important role in long-term shoreline evolution and high-frequency (or even permanent) flooding of low-lying areas, the synchronized action of high tides, storm surges and highly-energetic waves is projected to extensively contribute to the disrupting effects in living conditions along the Portuguese coastline (the reader is referred to the WP4.5/6 dynamical modelling report), potentially leading to the unavoidable infrastructural accommodation efforts, or even the abandonment of the shoreline long before permanent inundation takes place (Toimil et al., 2020). Future physical and human losses may become substantially greater than historical ones, in case no additional coastal protection and risk-reduction measures are implemented.

Adaptation measures have been implemented in Portugal since the 1950s, consisting mostly of hard defence structures, such as groins and seawalls, as well as artificial beach nourishment and sediment bypassing (essentially since the 1980s). The implementation of nature-based solutions has been gaining increased attention recently (Temmerman et al., 2013). Nevertheless, associated issues such as applicability and long-term cost-effectiveness (topics that are currently lacking in scientific literature), are a disadvantage in comparison with hard defence measures. Despite a slowly increasing interest in "greener" solutions by the global community (Brière et al., 2018; Van Loon-Steensma and Vellinga, 2019), the rate of increase in the extreme sea levels may be too high to simply consider nature-based approaches. According to Vousdoukas et al. (2020), the use of hard defence elements, such as dykes, will likely be unavoidable. Nevertheless, as of today, artificial near nourishment continues to be the measure of choice to maintain stable shoreline evolution in Portugal (Pinto et al., 2016; 2020; 2022). The latest Intergovernmental Panel for Climate Change (IPCC) Assessment Report (AR6; IPCC, 2022) considers beach nourishment as a nature-friendly solution, placed within the set of measures to reduce climate-change driven impacts on oceanic and coastal ecosystems. However, no consensus has yet been found for its efficacy as a long-term solution, due to increased financial costs and possible threats to local ecosystems (Schipper et al., 2021). Additionally, sustainability issues emerge, in terms of sediment availability, coastal geomorphology and environmental impacts. Furthermore, beach nourishment options require thorough legislation to avoid coastal development under "false protection" (Cooper et al., 2009; Pranzini et al., 2017; Parkinson and Ogurcak, 2018). According to Parkinson and Ogurcak (2018), artificial beach nourishments should continue to be a viable option during the next decades, but not as a long-term solution. Rather, it should be considered as a provisory measure, to gain time to implement more robust and long-term strategies, such as relocation.

As of today, protection and accommodation are the measures of choice to increase resilience of the Portuguese coastal areas against climate change. While construction is already profoundly limited in high-risk areas, according to the POOC/POC, this measure requires integration within the projections towards the end of the 21st century and further. Although relocation has already been conducted in Portugal (*e.g.*, Esmoriz and Praia de Faro), many doubts about its effectiveness in the short and medium-term arise, due to unclear legislation and the bureaucracies involved. Upon consultation of stakeholders, it was concluded that the revision of legislation related to the territorial management instruments along with its enforcement to safeguard infrastructures, communities and ecosystems in coastal areas, is a priority transversal measure requiring implementation in Portugal within the next decade. Nevertheless, as changes are expected to continue well beyond the end of the 21st century (Lyon et al., 2022), any measure of coastal protection must consider additional levels to be implemented in the longer-term (beyond 2100). In this context, relocation may be deemed ultimately necessary along the most vulnerable coastal urban areas.

The present report described the viable adaptation solutions for the Portuguese coast, from a national and local (Ofir, Costa Nova, Cova Gala, Costa de Caparica, Praia de Faro) perspective, in light of the expected inaction costs, in case no adaptation measures are considered. It summarized the current framework in terms of laws, plans and strategies being applied along the Portuguese shores, enumerating strategies that can provide erosional buffers to the most affected coastal areas. The solutions provided are balanced between hard structures (to be used as one of the last resources – the last being relocation) and nature-based solutions, which are strongly favoured, as is the case of beach nourishment and dune restoration. Other solutions, specifically legal ones, can be adopted at a national level and foster a change in the current paradigm in coastal management. The complementarity between local adaptation measures and wider political agenda is considered the best solution for coastal adaptation to climate change. Finally, the expected adaptation costs were estimated, in order to maintain the same level of coastal protection as of 2023.

The balance between inaction and adaptation costs allowed to conclude that generally the cost-benefit ratio of adaptation is low at a national scale (maximum values of 4928 million € for adaptation, and 14223 million € for inaction). Therefore, adaptation should be a pursued, from both a physical and socio-economic perspective. While the same conclusion is obtained for most of the Portuguese regions (districts, NUTSII and POC domains), locally, the expected adaptation costs can exceed the projected inaction ones. Specifically, in very densely urbanized coastal fronts, the adaptation costs related to the accommodation of pre-existing adherent structures or even the remaining infrastructures may saturate the cost-benefit ratio sooner than in the remaining coastal environments. In those instances, relocation (which may be progressive) is suggested, in shorter timeframes, ideally to start within the next 20 to 30 years. In other areas, such as in the Beja district, the adaptation costs largely outweigh inaction ones, in part due to the unconsidered indirect value of economic operations, such as in the Sines harbor. This vital infrastructure, which represents 1.5% of the Portuguese economy, could, by itself, be responsible for a quick increase in the projected total inaction costs if its operations were to be affected by episodic extreme events. A specific economic analysis, conducted locally, is recommended, not only in this case but also for densely urbanized coastlines, where tourism and other economic activities (unconsidered in the present analysis) may contribute to different adaptation cost-benefit ratios.

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