National Roadmap for Adaptation 2100

Portuguese Territorial Climate Change Vulnerability Assessment for XXI Century

REPORT

WP7 – Regional Adaptation Storylines

Final Version

National Roadmap for Adaptation 2100

Portuguese Territorial Climate Change Vulnerability Assessment for XXI Century

Title: RNA2100 – Regional Adaptation Storylines

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1.Introduction

Unequivocal climate change and impacts

Human-induced climate change, driven by greenhouse gas emissions and land use changes, is an undeniable reality, and it presents significant risks to both human societies and natural ecosystems (IPCC, 2013, 2021). As nowadays climate change moves beyond debating its existence to focus on assessing regional consequences and how to respond, there is a pressing demand for society to undergo transformation through strategies aimed at both reducing emissions and adapting to the changes already underway.

The world is witnessing an almost continuous acceleration in the number, speed and scale of broken climate records: 2023 was the warmest year on record, and since the beginning of the 21st century, new global average temperature records were set for 20 times since records exist (United Nations Environment Programme, 2023; NASA's Scientific Visualization Studio, 2024). The year of 2023 was 1.48°C warmer than the pre-industrial reference temperature (average 1850-1900), and since June 2023 every month establishes new ever-monthly records, e.g. September 2023 was the hottest month since records exist, exceeding the previous record by an unprecedented 0.5°C, and registering global average temperatures +1.8°C above pre-industrial levels (Copernicus Climate Change Services 2023a, 2023b). Nonetheless, this does not imply that the world has exceeded the 1.5°C temperature threshold aimed at the Paris Agreement, since this refers to global warming levels based on multi-decadal averages; but it does signal a sharping proximity. Furthermore, every increment of global warming results in rapidly escalating regional temperatures, changes in precipitation patterns, and most importantly, an increasing frequency and severity of extremes, such as heatwaves, droughts and extreme precipitation, with extensive implications for human livelihoods and ecosystems (IPCC, 2023). In the last few years, an unprecedented number and severity of climate extremes occurred, like extensive droughts, heatwaves, wildfires, heavy precipitation (Páscoa et al., 2021; Lorenzo et al., 2022; Dasari et al., 2014; Días-Poso et al., 2023; Bento et al., 2023; Santos et al., 2023; Ramos et al., 2018), etc, impacting directly and indirectly in society and ecosystems.

Recently, the European Environment Agency (EEA) released a report on the economic losses caused by weather- and climate-related extreme events in the European Union (EU) Member States between 1980 and 2022 (EEA, 2023). This report highlights the economic losses of assets estimated at 650 billion euros in the EU Member States, of which 52.3 billion euros corresponded to 2022 alone. The analysed period reveals an increase in economic losses over time, however acknowledging the fragility of this trend due to the large annual costs' variability and data limitations. For Portugal, in the same period 1980-2022, the total economic losses caused by weather- and climate-related extreme events is estimated at approximately 15 billion euros, which reveals a loss of ~163 euros per m^2 and ~1500 euros per capita, respectively.

Noteworthy is that insured losses correspond to only 535 million euros, arising from the extremely small insured losses of ~4% in Portugal, one of the lowest amongst the 27 EU members.

The PESETA study constitutes the state-of-the-art of economic analysis of selected climate impacts at the European scale (PESETA IV, 2020). In this study, the economic impacts in terms of welfare were quantified for seven climate impact categories: river floods, coastal floods, agriculture, energy supply, droughts, windstorms and human mortality. At the European scale, the total related welfare loss due to climate change for the included categories would reach 36, 65 and 122 billion euros at 1.5ºC, 2ºC and 3ºC global warming levels (GWLs), respectively. The projected welfare loss (% GDP) due to climate change is strikingly heterogeneous over Europe, with no projected changes or rather small decreases (up to 0.5% for the GWL of 3ºC) in the northern European welfare, to a maximum estimated impact for all the GWLs for Southern Europe. In fact, the expected welfare loss for Southern Europe is of -0.73%, -1.36% and -2.78% for the 1.5ºC, 2ºC and 3ºC GWLs, respectively.

Plausible futures

At the time the National Roadmap for Adaptation 2100 (RNA2100) assessment begun, there were not (and there are still not today) available regional climate simulations forced by the Earth System and Global Climate Models of the Coupled Model Intercomparison Project (CMIP) Phase 6, which obviously constrained the use of the European Coordinated Regional Climate Downscaling Experiment (EURO-CORDEX)[1] Phase I runs, following the CMIP5 specifications and therefore its concentration scenarios - the Representative Concentration Pathways (RCPs; Moss et al., 2010; van Vuuren et al., 2011; Riahi et al., 2011) and not the Shared Socioeconomic Pathways (SSPs; O'Neill, 2016) developed later for CMIP6. These two scenario sets are similar but with some relevant differences in the future greenhouse gases emissions (GHG) time evolutions, aerosols and land-use, and thus global warming projections (IPCC 2014, 2021).

In the framework of the CMIP5 (Taylor et al., 2012) and the International Panel for Climate Change (IPCC) Fifth Assessment Report (AR5), the RCP scenarios, RCP2.6, RCP4.5 and RCP8.5 were developed, for GHGs, aerosols and land-use/land-cover. The RCPs are designated according to the correspondent effect

[1] The EURO-CORDEX is the European branch of the international CORDEX initiative, aiming for an internationally coordinated framework to produce improved regional climate projections for all land regions worldwide. The CORDEX results provide input for climate change impact and adaptation assessments within the timeline of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) and beyond.

of greenhouse gases concentrations in the radiative forcing[2] values in the year 2100: increases relative to pre-industrial of +2.6 W/m^2, +4.5 W/m^2 and +8.5 W/m^2 for the RCPs 2.6, 4.5 and 8.5, respectively. The RCP2.6 is a mild scenario and the RCP8.5 is the high-end scenario. The first assumes that global annual greenhouse emissions peaked between 2010 and 2020, while for the RCP4.5 emissions are projected to peak around 2040 and diminish afterwards, and for the RCP8.5, emissions are projected to increase throughout the twenty-first century (Moss et al., 2010; van Vuuren et al., 2011; Riahi et al., 2011). Within the present document, these scenarios are also referred assuming their qualitative characteristics of mitigation, following the Paris Agreement (RCP2.6), intermediate conditions (RCP4.5) and "worst-case" or high-end scenario (RCP8.5). More recently, in the framework of the CMIP6 and the IPCC Sixth Assessment Report (AR6, IPCC, 2023), the SSP–RCP scenarios were developed (O'Neill et al., 2016). The four main SSP–RCPs are SSP1–2.6, SSP2–4.5, SSP3–7.0 and SSP5–8.5, where the radiative forcing is also defined as in the RCPs. In Figure 1.1, a comparison of the CO_2 total emissions and projected global warming evolutions by the IPCC, linked to the RCP and SSP scenarios, is displayed.

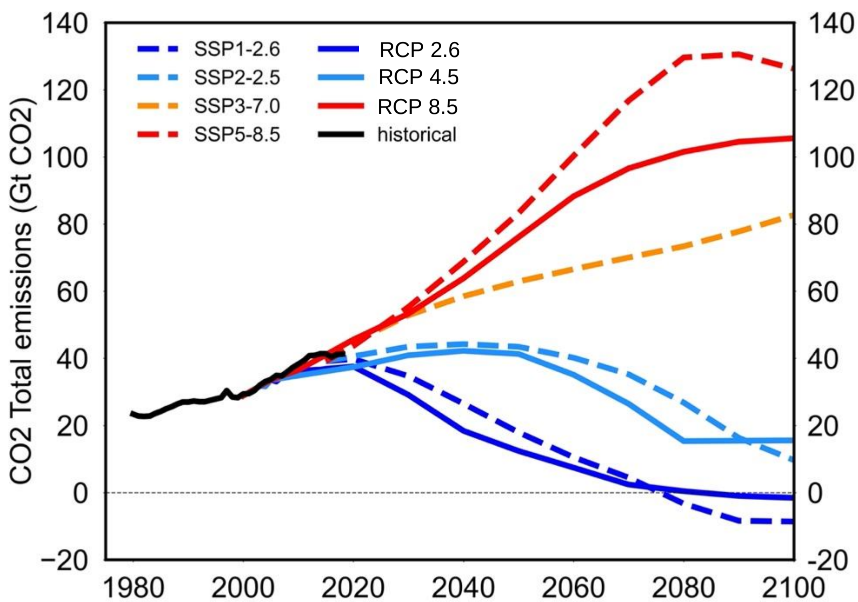


Figure 1.1 - CO2 total emissions for the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) scenarios, from CMIP5 and CMIP6, respectively.

Since the design of the RCPs and SSPs, important modifications in international mitigation policies took place, which arose suggestions and evidence that the upper-end scenarios, such as the RCP8.5 and the SSP5–8.5, are highly unlikely (Hausfather and Peters 2020; and Pielke jr; Climate Action Tracker). As it

[2] The change in the net, downward minus upward, radiative flux (expressed in W/m^2) due to a change in an external driver of climate change, such as a change in the concentration of carbon dioxide (CO_2), the concentration of volcanic aerosols, or in the output of the Sun (IPCC AR5).

can be seen in Figure 1.2, the global warming evolution projected according to the RCP8.5 is close to the one linked with the SSP5-8.5 and above the SSP3-7.0, being the latter increasingly seen as the high-end scenario due to the global mitigation effort and policies envisaged to comply with the Paris Agreement. Importantly, future projections for the RCP4.5 and the SSP2-4.5 indicate global warming values slightly above 2.5 ^{o}C by 2100.

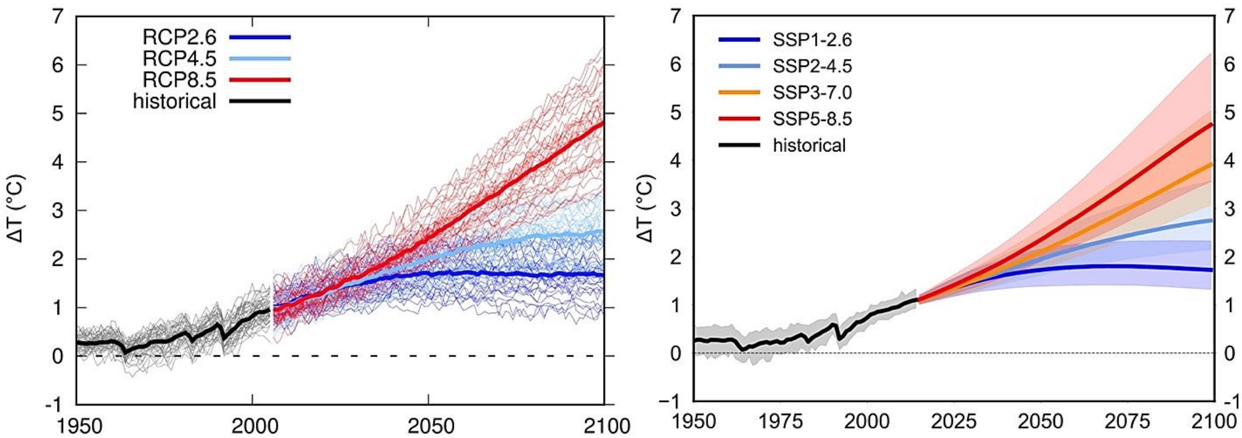


Figure 1.2 – (a) Global surface temperature changes between 1950-2100 as a difference to the 1861-1900 period, from IPCC 5th Assessment Report WGI Summary for Policy Makers report, and (b) Global surface temperature changes between 1950-2100 as a difference to the 1850-1900 period, from the IPCC 6th Assessment Report WGI Summary for Policy Makers report.

The recent trends on global emissions can be showcased by the new record of global GHG emissions in 2022 (still unknown if it is broken again in 2023) and, at least, the increase of global energy-related CO_2 emissions in 2023. Considering the 57.4 Gt (billion tonnes) global GHG emissions in 2023, an increase of 1.2% against 2022 was registered (UNEP, 2023). Furthermore, the International Energy Agency reported that the global energy-related CO_2 emissions grew by 1.1% in 2023, to reach a new record high of 37.4 Gt. This compares with an increase of 490 Mt (million tonnes) in 2022 (+1.3%; IEA, 2024). Emissions from coal accounted for more than 65% of the increase in 2023. As it stands, the complete implementation of unconditional Nationally Determined Contributions (NDCs)[3] pledged under the Paris Agreement would steer the world towards limiting the temperature increase to 2.9°C above pre-industrial levels, by the end of this century. If conditional NDCs were also fully implemented, the temperature rise could be further reduced to 2.5°C (UNEP, Emissions Gap Report 2023). The Climate Action Tracker projects a median global warming of 2.7°C for 2100 based on current policies and 2.5°C based on 2030 NDC targets (Climate Analytics and NewClimate Institute, 2023). According to both Figures 1 and 2, it is fair to assume that the

[3] These are the commitments made by individual countries to reduce greenhouse gas emissions and adapt to climate change. Each country sets its own NDC based on its national circumstances, capabilities, and priorities. The NDCs are submitted by countries as part of their participation in the Paris Agreement and are intended to be updated and enhanced over time.

global warming is evolving in a rough agreement with the emission scenario RCP4.5 (SSP2–4.5) and way below the RCP8.5 (SSP3–7.0) from CMIP5 (CMIP6) (Figure 1.3).

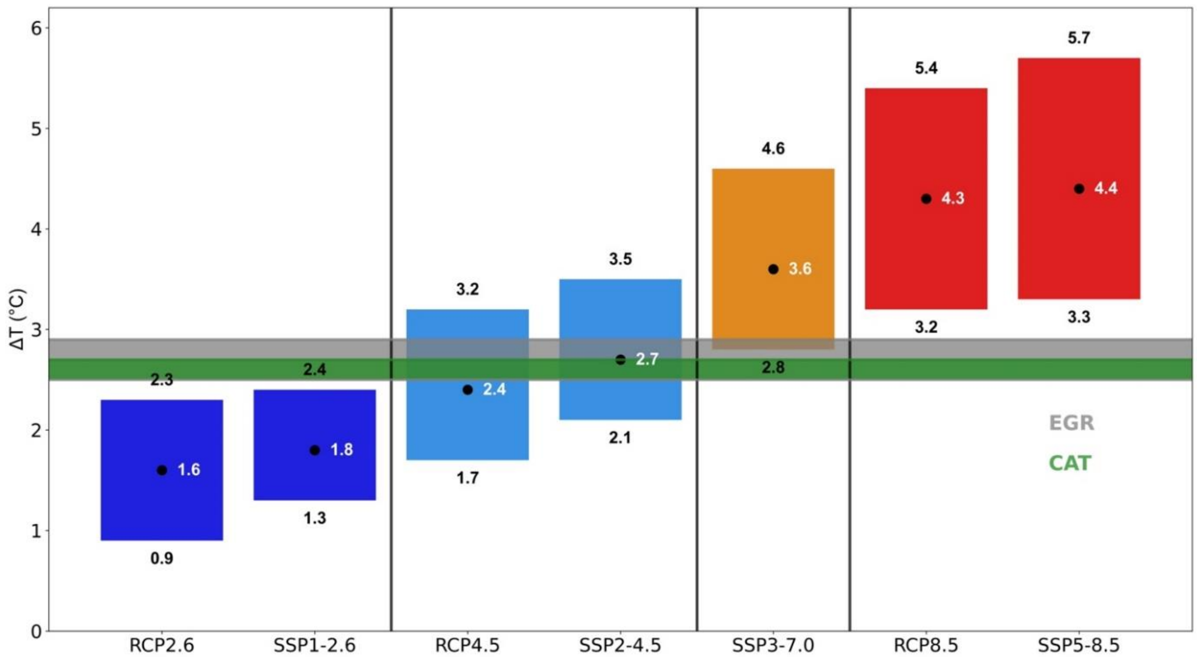


Figure 1.3 – Global warming projections under emissions scenarios from the IPCC AR5 and AR6 reports, for 2081-2100 relative to 1850-1900. Dots show best estimates and columns show the range of uncertainty assessed as likely for the AR5 RCP scenarios and very likely for the AR6 SSP-RCP scenarios. Source: IPCC (2014) and (2021). The horizontal bars show the Emissions Gap Report (EGR) and Climate Action Tracker (CAT) warming values by 2100 (see text). Adapated from Highcharts by Carbon Brief.

Finally, some authors point out that is rather early to discard high-end scenarios (e.g., SSP3-7.0 or RCP8.5; Schwalm et al., 2020), due to the distinctiveness of some scenarios (e.g. SSP3–7.0; Shiogama et al., 2023), and high uncertainties linked to unresolved climate system processes and non-linear feedbacks, such as the artic amplification, recent unprecedented increases of methane emissions, etc, and shortcomings in the understanding and modelling of extremes, such as the western European heatwaves trends (Vautard et al., 2023), etc. Furthermore, some scientists defend the inclusion of high-end scenarios as well, as a way of accountability and acceleration of mitigation efforts. Finally, Shiogama et al (2023) and others, stress that when the SSP3–7.0 is used as the possible upper-end scenario for impact assessments, recommendations are clear that impacts, adaptation and vulnerability researchers also perform impact model simulations under SSP5–8.5.

Based on the initial design of the project, and on uncertainties still found in scientific literature and common practice from previous studies, this report includes three RCP scenarios (RCP2.6, RCP4.5 and RCP8.5). Nevertheless, recognizing the recent internationally pursued efforts to reduce GHG emissions, which render the RCP4.5 as the more plausible scenario, and therefore here considered as baseline when referring to future impacts. Nonetheless, recognizing the existence of the large political and climate system uncertainties towards the end of the 21st century, the two other scenarios (RCP2.6 and RCP8.5) are also considered, for the lower and upper emission thresholds.

Additionally, due to uncertainties in the trajectory of emissions that the world will follow until the end of the century and in climate projections, there is an urgent need to stablish proper monitoring frameworks to adjust the timeframe in which each measure or set of measures should be implemented, so as to avoid maladaptation.

Portuguese climate and Adaptation

Portugal Mainland lies within the Mediterranean basin, in the transition zone between the arid to semiarid subtropical, and the humid climates of northern Europe, being very sensitive to changes in global climate. Indeed, it has been identified as a climate change "hotspot", with observed and projected rates of climate change exceeding global trends for most variables (Giorgi 2006; Lionello and Scarascia 2018; Cramer et al., 2018; Soares et al., 2022). Indeed, Portugal's vulnerability to climate impacts is being increasingly recognized in policy circles. During the European Council meeting in December 2019, President von der Leyen stated that "Portugal is one of the countries most affected by climate change".

As warming and drying future conditions may significantly affect the human and natural environment in Portugal, the climate risks and vulnerabilities assessments are key to support adaptation strategies. In this context, the National Roadmap for Adaptation 2100 (RNA2100) aims to provide scientific support to adaptation policy exercises by (1) identifying and characterising climate change impacts on the most vulnerable domains in Portugal Mainland; (2) characterising socioeconomic impacts on different territorial scales and assess financial needs; and (3) contributing to the implementation of a National Spatial Planning Policy Programme, by identifying and mapping vulnerable territories to climate change. The most vulnerable domains focused by the RNA2100 include the coastal regions, water resources/agroforestry and wildfires. To effectively reach targeted audiences, the RNA2100 defines adaptation narratives for each Portuguese *Nomenclatura das Unidades Territoriais para Fins Estatísticos* (NUTS) II[4] region.

Adaptation storylines

Although climate modelling is currently the primary source of knowledge on future climate change, from the global to the regional level, the associated uncertainties can quickly accumulate to a point where they

[4] Considering the 2013 Portuguese configuration of the NUTSII, i.e. Norte, Centro, Área Metropolitana de Lisboa, Alentejo and Algarve regions.

hinder rather than support scenario-based climate adaptation decision-making (Wilby and Dessai, 2010). Alternative approaches to investigate future climate change and adaptation are thus emerging, not seeking to quantify probabilities, but instead to develop descriptive "narratives", "storylines" or "tales" of plausible future climates or adaptation and impact mitigation strategies. The term "narrative" is often used by social scientists to characterize peoples' views, understandings, or perspectives. Narrative analysis is used to investigate climate change discourses and the framing of climate change by the media, policymakers or other stakeholders, giving emphasis on qualitative understanding rather than quantitative accuracy.

Within this context, adaptation narratives (or pathways) have been proposed as a promising decision-focused approach to incorporate flexibility into decision-making and account for future uncertainties (e.g. Haasnoot et al., 2013; Wise et al., 2014; Bosomworth et al., 2017). Adaptation pathways are broadly understood as sequences of actions, which can be implemented progressively, depending on future dynamics. In an adaptive plan, adaptation pathways capture the implementation process by specifying which measure(s) are to be taken now and which are planned to be implemented once certain conditions occur (Kwakkel et al., 2016). As such, adaptation pathways explicitly consider uncertainty and embed flexibility within planning.

The RNA2100 follows **three stages**: regional climate scenarization, biophysical impacts for a number of sectors and hazards (named impact categories), and the economic analysis of selected impacts. The future projected climate for Portugal was characterized using a weighted multi-model ensemble based on the EURO-CORDEX simulations (Jacob et al., 2020), produced at 12 km resolution (Lima et al., 2023a,b). One **historical present climate** period **(1971-2000)** and three **future periods (2011-2040, 2041-2070, 2071-2100)**, **under three different scenarios (RCP2.6, RCP4.5 and RCP8.5)**, were considered. The biophysical impact modelling was performed for four climate impact sectors: **coastal erosion and flooding, forest fires, water and agroforestry systems**. Additionally, to the arguments previously presented about the use of the RCPs, being Portugal in a climate transition region, the expected changes show a higher degree of uncertainty and impact, and therefore, including a multi-scenario approach is crucial for assisting decision making in national context with a strategic view.

In this report, corresponding to Work Package (WP) 7 (WP7A), sectoral adaptation narratives are proposed, in articulation with the results from the WP4 "Sectoral Impacts and Modelling" and WP5 "Adaptation Needs and Economic Analysis" reports, focusing on the identified risks related to climate change, namely **water scarcity and stress on crops, coastal erosion and flooding, forest fires, and the associated economic losses**. These are geographically organized by means of the 2013 Portuguese configuration of the NUTSII territorial division system, incorporating five regions, namely **Norte**, **Centro**, **Área**

Metropolitana de Lisboa, **Alentejo and Algarve**. Each narrative identifies the present and future vulnerabilities for each region, in articulation with the impact modelling results from WP4. It highlights the adaptation measures identified for each sector, proposing structures for their territorial implementation, and focusing on the inaction and adaptation economic costs, from WP5. Implementation opportunities within the current IGTs (Territorial Management Instruments - *Instrumentos de Gestão do Território*) are also identified.

The structure of the report is as follows: in section 2, the proposed adaptation narratives are presented, for each climate impact sector, at each NUTSII region. The respective summary cards are offered in section 3. In section 4, the final remarks and conclusions are presented.

2.Adaptation Narratives

2.1. Norte

2.1.1. Climate projections

The Norte region is projected to experience more significant warming compared to the global average and to the other Portuguese NUTS II regions. Projections indicate a more pronounced warming in summer than in winter, and larger for maximum than minimum temperature, across all climate scenarios. In the RCP4.5 scenario, the Norte region is projected to undergo temperature rises of 1.9 – 2.6 ºC (Figure 2.1 and Table 2.1). Even under the RCP2.6 scenario, an increase in annual temperature of 1.4 ºC is expected during the 21st century. Conversely, under the RCP8.5 scenario, temperature increases of +4.4 ºC and +4.8 ºC are foreseen for minimum and maximum temperature, respectively, by the end of the 21st century.

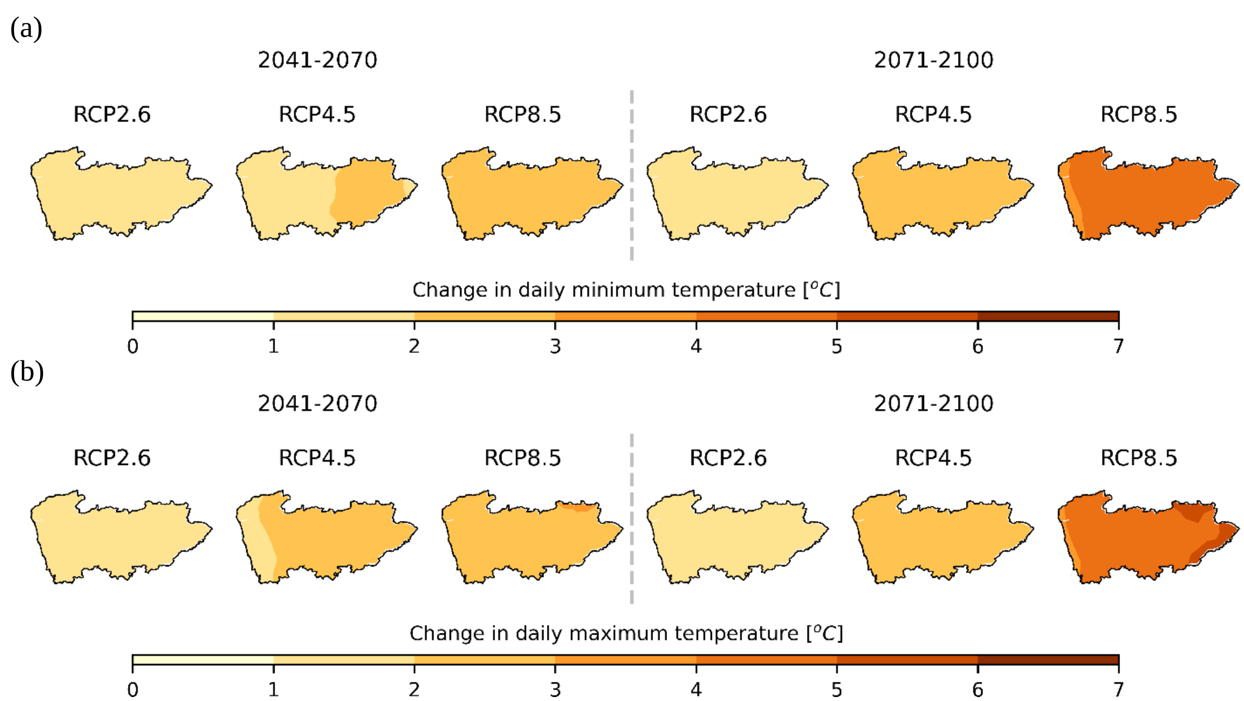


Figure 2.1 – Future projected changes in daily (a) minimum and (b) maximum temperature (ºC) for the Norte NUTS II region.

Table 2.1 – Climatological annual mean daily minimum (Tn) and maximum (Tx) temperature (ºC) for the reference period (Historical – 1971-2000); and, future projected changes in daily minimum and maximum temperature (ºC) for the Norte NUTS II region.

Norte	1971-2000	Differences	2041-2070			2071-2100		
	Historical		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
T_n (°C)	7.0	ΔT_n (°C)	1.4	1.9	2.6	1.4	2.5	4.4
T_x (°C)	17.1	ΔT_x (°C)	1.5	2.1	2.8	1.4	2.6	4.8

Changes in precipitation are greatly dependent on the season and the future emission scenario. Future projections suggest a decline in mean precipitation over the course of the 21st century under RCP4.5 and RCP8.5, and a small increase under RCP2.6 scenario (Figure 2.2 and Table 2.2). Significantly, the RCP4.5 scenario portrays a small decline in annual precipitation, with projected reductions of around -3% by the end of the 21st century. For the RCP2.6 scenario, the precipitation changes are small, fluctuating around +2%. For the RCP8.5 scenario, the projections point to an annual decrease exceeding -15% by the end of the century.

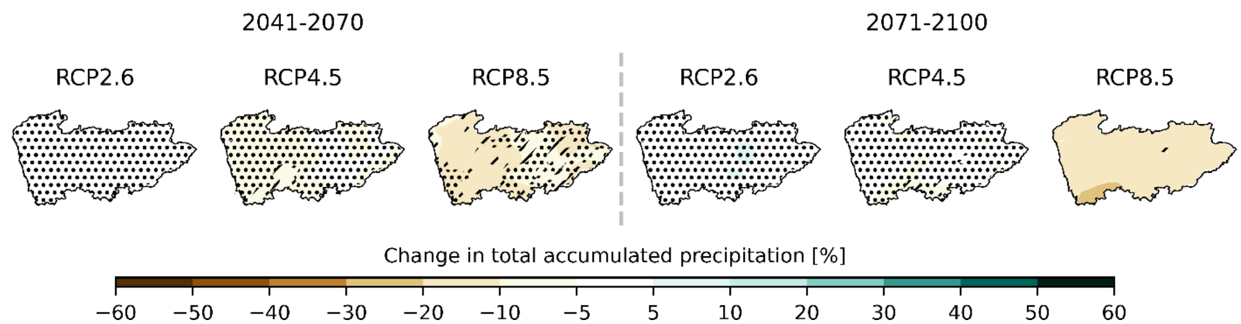


Figure 2.2 – Future projected relative changes in annual accumulated precipitation (%) for the Norte NUTS II region. Grid-points where the precipitation does not specify changes statistically significant are identified by dotted hatching.

Table 2.2 – Climatological annual mean accumulated precipitation (Pr) (mm) for the reference period (Historical – 1971-2000); and, future projected relative/absolute changes in annual accumulated precipitation (%/mm) for the Norte NUTS II region.

Norte	1971-2000	Differences	2041-2070			2071-2100		
	Historical		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
$Pr\ (mm)$	1420.0	ΔPr (%)	2.0	-6.2	-10.5	2.8	-3.3	-16.3
		$\Delta Pr\ (mm)$	16.6	-93.8	-151.4	30.3	-61.5	-238.2

As a result of the warming, the frequency and intensity of extreme temperatures is projected to change significantly, in less (more) pronounced way under the RCP2.6 (RCP8.5) scenario (Figure 2.3). Concurrent with the rise in maximum temperatures, the occurrence of hot days[5], as well as summer[6] and extremely hot days[7], is projected to escalate. In the historical period (1971-2000), the number of hot days ranges between 0 and 40 days. For the RCP4.5, more 30 hot days are expected at the end of the century. For the RCP2.6, the increase is around 15 days, but for the RCP8.5 the number of hot days is projected to increase around 60 days when compared to the historical period. Furthermore, heatwaves[8] are projected to become more frequent, intense, and longer lasting. In the historical period 1 to 2 heatwaves occur per year with a mean duration around 6 days per event. Under the RCP4.5, it is expected an increase in the number of heatwaves between 4 and 6 throughout the 21st century. Even under the RCP2.6, the occurrence of more up to 3 heatwaves per year is projected. However, considering the RCP8.5, the projections point to more 9 heatwaves per year. Aligned with the increase in the number of heatwaves, the mean duration of these events is also projected to increase. For the RCP4.5, the mean duration of heatwaves is projected to increase around 2 days. A similar result is expected for the RCP2.6, whilst under the RCP8.5, the expected increase is between 3 and 6 more days in heatwave, when compared with the historical period. Aligned with the rising of minimum temperature, tropical nights[9] are expected to become more prevalent, while the incidence of cold days[10] will diminish. For the RCP4.5, the tropical nights are projected to grow up to more 30 nights, and for the RCP8.5 there is a large spatial heterogeneity on the projected increases, which can escalate more 60 nights.

[5] Hot days: number of days where maximum temperature exceeds 30ºC.
[6] Summer days: number of days where maximum temperature exceeds 25ºC.
[7] Very hot days: number of days where maximum temperature exceeds 35ºC.
[8] Heatwave is defined as a period of five or more consecutive days with maximum temperature above the 90th percentile.
[9] Tropical nights: number of days where minimum temperature exceeds 20ºC.
[10] Cold days: number of days where minimum temperature is below 7ºC.

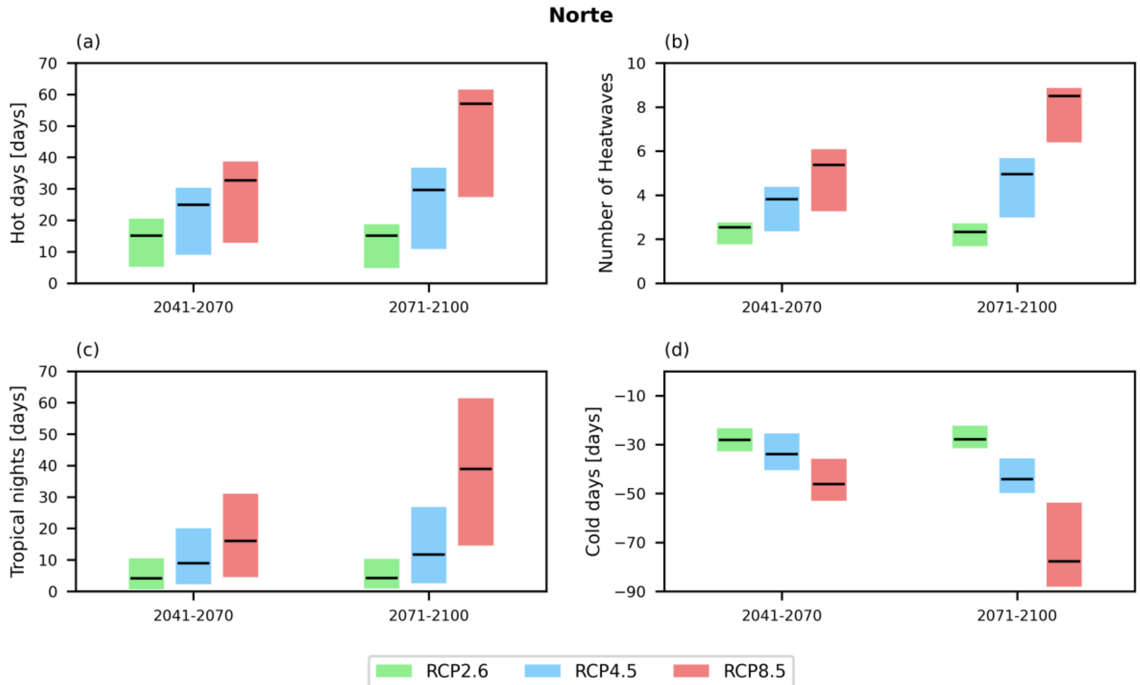


Figure 2.3 – Distribution of the projected changes in (a) hot days [days/year], (b) number of heatwaves per year, (c) tropical nights [days/year] and (d) cold days [days/year] for all gridpoints in Norte's region. The straight black line represents the mean value for the Norte's region. Individual boxes span from the spatial minimum to the maximum value of the Norte's region.

In line with the decline in mean accumulated precipitation, a reduction in the number of wet days[11] and, consequently, an increase in the number of dry days, is projected until the end of the 21st century (Figure 2.4). For the RCP4.5 scenario, less 10 wet days are projected throughout the 21st century. For the RCP2.6 scenario, however, is expected to have negligible changes throughout the century, with a slight decrease for the mid- and end-21st century of around 5 wet days. For the RCP8.5 scenario, the projections point to less 30 wet days in the end of the 21st century. Regarding the number of days with moderate[12] and heavy[13] precipitation, clear projected reductions are evident, especially under the RCP4.5 and RCP8.5 scenarios. Consequently, the number of consecutive dry days[14] is expected to increase, enhancing drying conditions. Conversely, the maximum 5-day accumulated precipitation[15] is projected to increase especially over the western part of the Norte's region. Under the RCP4.5 scenario, the increases can reach more 120 mm over the area of Peneda-Gerês National Park (in the historical period the maximum 5-day accumulated precipitation is around 600 mm). The results for the RCP2.6 scenario are similar to the ones for the RCP4.5. For the RCP8.5 scenario, the increase of maximum 5-day accumulated precipitation can reach more 170

[11] Wet days: number of days with precipitation exceeding 1 mm/day.
[12] Moderate precipitation days: number of days with precipitation exceeding 10 mm/day.
[13] Heavy precipitation days: number of days with precipitation exceeding 20 mm/day.
[14] Dry days: number of maximum consecutive dry days where precipitation is below 1 mm/day.
[15] Maximum of 5-day accumulated precipitation.

mm. In spite of the projected decrease of the number of wet days, projections suggest a concentration of rainfall into shorter time frames, implying an intensification of moderate/heavy precipitation regardless of the scenario.

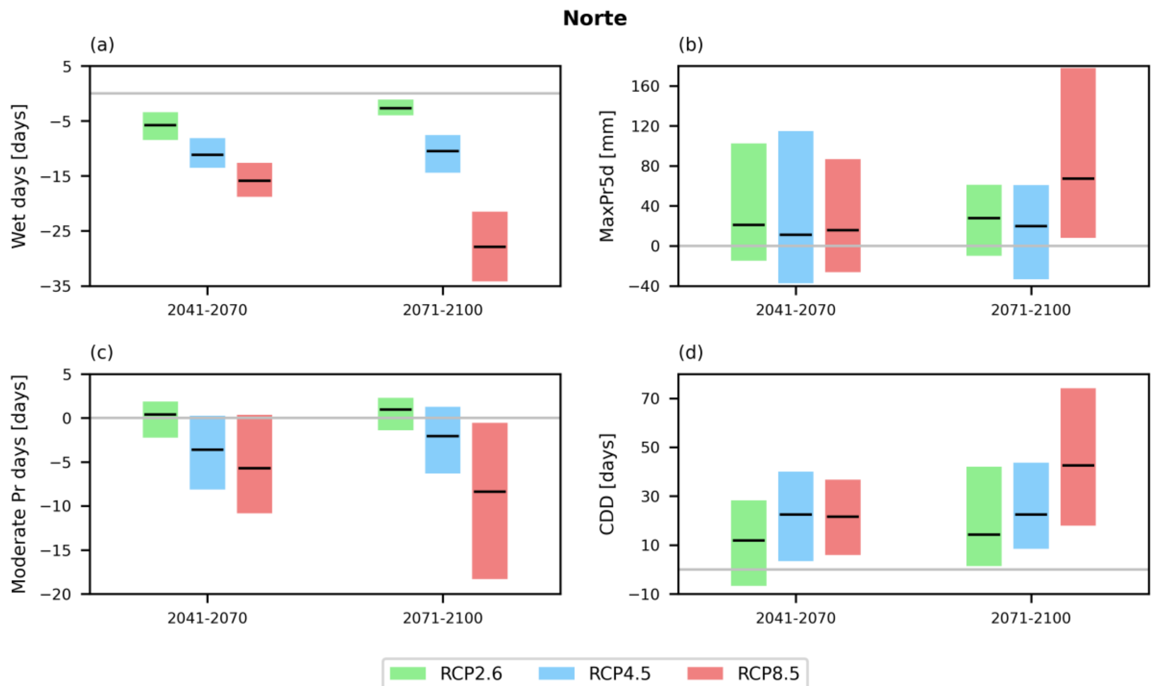


Figure 2.4 – Distribution of the projected changes in (a) wet days [days/year], (b) maximum of 5-day accumulated precipitation (MaxPr5d) [mm], (c) moderate precipitation days [days/year] and (d) consecutive dry days (CDD) [days] for all gridpoints in Norte's region. The straight black line represents the mean value for the Norte's region. Individual boxes span from the spatial minimum to the maximum value of the Norte's region.

A summary of confidence in the direction of projected changes in climate means and indices is presented in Table 2.3. The results give us confidence in climate projections presented here.

Table 2.3 – Summary of confidence in the direction of projected change in climate means and indices for the Norte NUTS II region. Temperature: climatological annual mean daily minimum (Tn) and maximum (Tx) temperature, hot days (Txg30), number of heatwaves per year (HWN), tropical nights (Tng20) and cold days (Tnl7); Precipitation: climatological annual mean accumulated precipitation (Pr), wet days (Prg1), maximum of 5-day accumulated precipitation (MaxPr5d), moderate precipitation days (Prg10) and consecutive dry days (CDD). A standard deviation of 0.25, 1, 2, 3 corresponds to a moderate, strong, very strong, severe increase/decrease of the variables. Values shown are ensemble median changes. Colours illustrate the model's agreement within the multi-model ensemble.

Norte							
		2041-2070			2071-2100		
		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Temperature	Tx	↑↑	↑↑↑	↑↑↑	↑↑	↑↑↑	↑↑↑
	Txg30	↑	↑↑	↑↑↑	↑	↑↑↑	↑↑↑
	HWN	↑↑	↑↑↑	↑↑↑	↑	↑↑↑	↑↑↑
	Tn	↑↑	↑↑↑	↑↑↑	↑↑	↑↑↑	↑↑↑
	Tnl7	↓↓	↓↓	↓↓↓	↓↓	↓↓↓	↓↓↓
	Tng20	↑	↑↑↑	↑↑↑	↑	↑↑↑	↑↑↑
Precipitation	Pr	⊠	↘	↘	⊠	⊠	↘
	MaxPr5d	↗	↗	↗	↗	↗	↑
	Prg1	↘	↘	↓	⊠	↘	↓
	Prg10	⊠	↘	↘	⊠	⊠	↘
	CDD	↗	↑	↑	↑	↑	↑↑↑

↑↑↑	Change above 3 standard deviations
↑↑	Change above 2 standard deviations
↑	Change above 1 standard deviation
↗	Change above 0.25 standard deviations
⊠	Change between -0.25 and 0.25 standard deviations
↘	Change below -0.25 standard deviations
↓	Change below -1 standard deviation
↓↓	Change below -2 standard deviations
↓↓↓	Change below -3 standard deviations

	High agreement: at least 80% of models show a positive change
	Low agreement: at least 50% of models show a positive change
	No agreement: models disagree on the direction of change
	Low agreement: at least 50% of models show a negative change
	High agreement: at least 80% of models show a negative change

2.1.2. Water scarcity and stress on crops

NUTS II Norte includes, within its administrative boundaries, four River Basins, where RH1 – Minho e Lima, RH2 – Cávado, Ave e Leça, and RH3 – Douro stands out (Figure 2.5). Among the hydro-agricultural developments existing in this region, only the one in Macedo de Cavaleiros stands out, with the water source being the Azibo reservoir. This hydro-agricultural development is the only one in the region that has a reservoir with a volume greater than 10 hm^3.

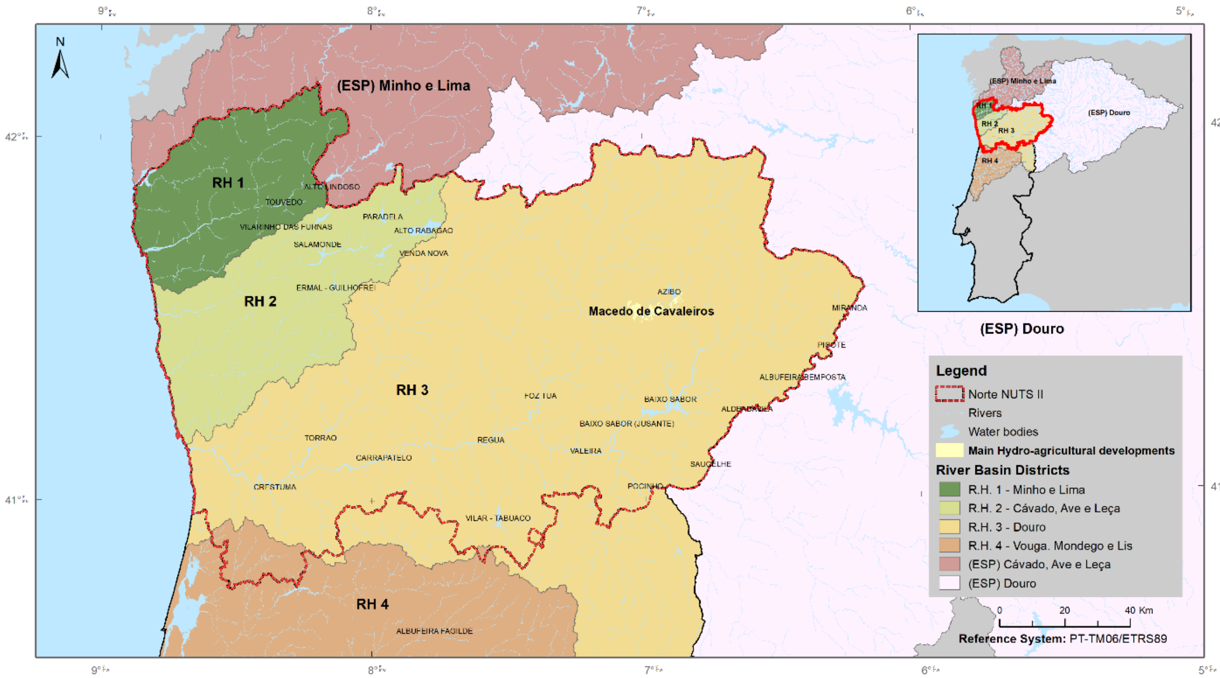


Figure 2.5 – NUTSII Norte and River Basins location: RH1 – Minho e Lima, RH2 – Cávado, Ave e Leça, RH3 – Douro and RH4 - Vouga, Mondego e Lis.

In 2022, the Norte region was the leading national producer of forage crops, namely maize, and main nuts, and seeds, contributing with 30.7% and 23.9%, respectively, to the country's total production in these crops. Forage crops gain even more importance as they correspond to 71.1% of the region's total productivity, with maize being the main crop (65.1%). The second most important crop is wine grapes, accounting for 11.3% of the total productivity in tons in the region.

Considering the full area of the principal River Basins that cross NUTS II Norte, climate change scenario projections indicate a decrease in water yield for the RCP4.5 scenario in the period 2041-2070, more significantly for RH3. This decrease loses significance towards the end of the century in the same scenario (Figure 2.6). The trend of decreasing water yield becomes more pronounced for the scenario with higher concentrations of greenhouse gases in the atmosphere (RCP8.5), with losses that can reach almost 2000 hm^3 on average per year by the end of the century. However, if concentration levels follow those outlined in the Paris Agreement throughout the 21st century (RCP2.6), the projections from the mid-century onwards show no significant changes in water yield with a slight increase in RH3. Nevertheless, it is essential to highlight that this does not necessarily imply a reduction in water stress levels within the region. The dynamics of water stress depend on balancing water availability with demands. The Water Exploitation Index plus (WEI+) is a ratio comparing water use to renewable water resources and serves as a common tool in the European Union and Portugal for assessing this equilibrium.

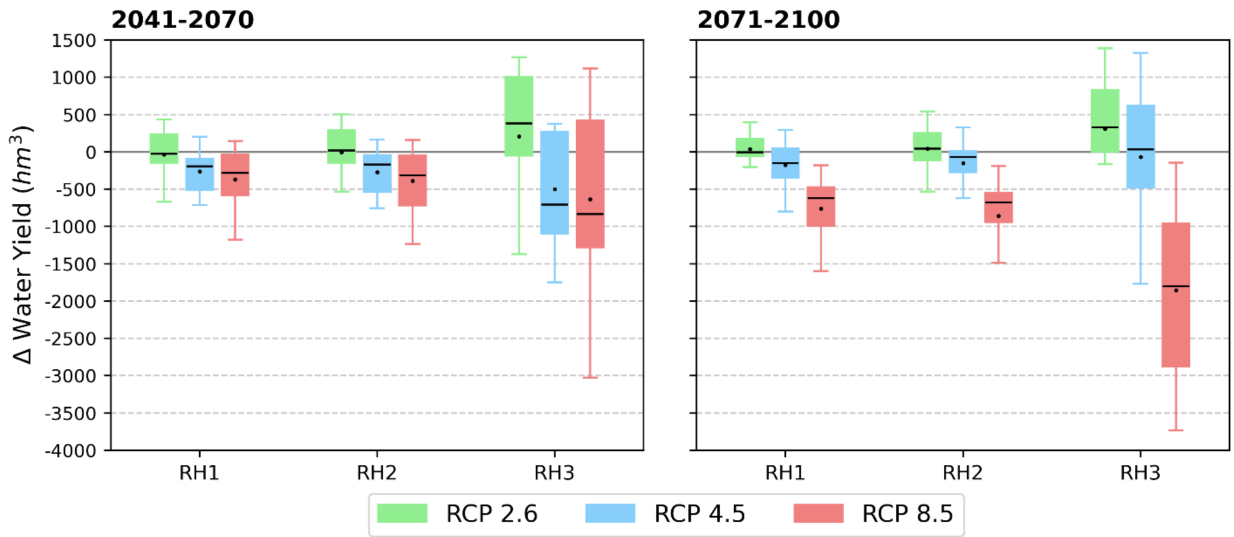


Figure 2.6 – Projected changes in averaged water yield (hm^3) for River Basins RH1 – Minho e Lima, RH2 – Cávado, Ave e Leça, and RH3 – Douro. Two future periods are shown: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5 and RCP8.5. The black line represents the ensemble median.

The Water Exploitation Index plus for the three River Basins Districts within NUTS II Norte is presented in Figure 2.7, indicating minimal changes under the RCP4.5 scenario compared to the present situation. Even under the RCP8.5 scenario, the increase in this ratio is relatively low, ranging between an anomaly of +0.5 and +4 percentage points. Regarding the RCP2.6 scenario, the projected changes show no significant difference when compared with the historical situation.

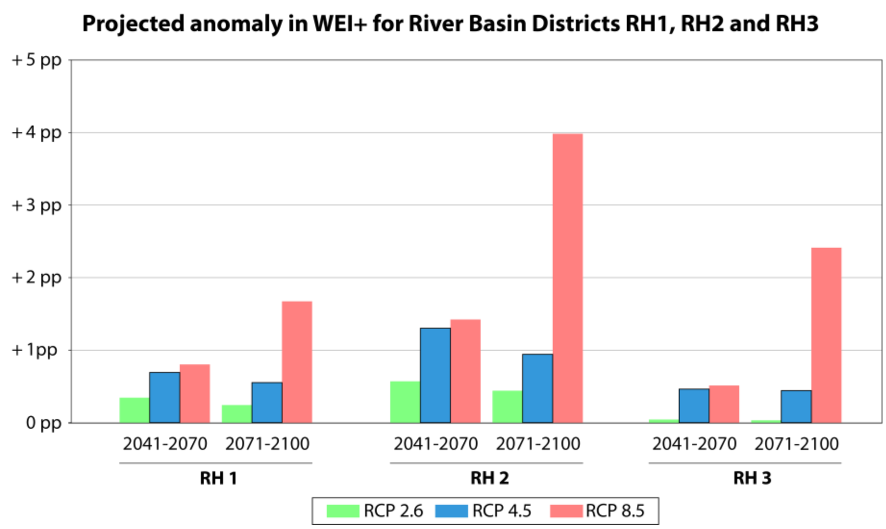


Figure 2.7 – Projected change in WEI+ (in percentage points) for River Basins RH1 – Minho e Lima, RH2 – Cávado, Ave e Leça, and RH3 – Douro. Two future periods are shown: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5 and RCP8.5. The presented values refer to the ensemble median.

Climate change can affect both irrigation requirements and productivity of the main crops grown in mainland Portugal. Table 2.4 illustrates these impacts on four crops: corn, vineyards, potato, and olive grove, representing 68.5%, 11,3%, 2,9%, and 1.9% of the crop's productivity considered in NUTS II Norte.

For olive grove, relative stability is observed across various climate change scenarios. However, a trend of decreasing productivity is noted for grape, corn, and potato, which could lead to a production decrease of up to -19.6% in the case of potatoes in RCP4.5, compared to current productivity levels.

Considering all costs and benefits due to climate change in crops, the overall economic losses can amount to more than 75 million euros per year for the time frame 2041-2070 and for the period 2071-2100 in RCP4.5. Economic losses in productivity are related to modifications in climatic conditions for the crops currently developed in the region due to changes in plant phenology.

Table 2.4 – Projected changes in productivity in average % for corn, olive grove, grape, and potato in NUT II Norte for two future periods: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5 and RCP8.5. The presented values refer to the ensemble median.

NUTS II Norte	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Corn	-2.1%	-7%	-9.3%	-6.5%	-7.8%	-14.2%
Grape	-1.2%	-2.2%	-2.2%	0.1%	-1.8%	-3.5%
Potato	-10.2%	-16.7%	-21.2%	-11.9%	-19.6%	-27.3%
Olive grove	-0.2%	-0.7%	-1%	-0.2%	-0.8%	-1.4%

Apart from the need for a careful assessment for the construction of new reservoirs, with updated meteorological and hydrological information, considering compliance with the DNSH (Do No Significant Harm) principle and also, proof that it continues to be an option in climate change scenarios (climate-proof), ensuring resilience now and in the future, it is imperative, firstly, to make a strong commitment to efficiency measures. Action should therefore consider minimizing losses to insignificant levels, reducing natural water consumption, which can be replaced in part by alternative sources such as water for reuse, changing crops to crops more adapted to existing conditions, among others. Therefore, the exercise presented focuses on identifying measures that allow the effects of the increase in the scarcity index, which currently exists, to be nullified throughout the 21st century and for different climate scenarios, through solutions that essentially affect the demand side.

To adapt the NUTS II Norte region to the projected impacts of climate change on water and agroforestry sectors, it is proposed that initial measures to be implemented should be of the no-regrets type, notably promoting the reduction of losses in the distribution network in hydro-agricultural developments and increasing irrigation efficiency throughout the region. Currently, the reality in the hydro-agricultural developments of the region varies significantly. For example, hydro-agricultural developments like Alfândega da Fé report 10.8% of losses in the distribution network, while others, namely Macedo de

Cavaleiros or Burgães report losses of 30.8% or 40%, respectively. This measure proposes that all irrigation perimeters achieve distribution network efficiency levels exceeding 90%.

In terms of irrigation efficiency, it is assessed that all irrigation in applicable crops transition to using drip irrigation systems, where irrigation efficiency typically ranges between 90-95%. In the Norte region, the adoption of this irrigation method for forage crops would be particularly relevant. Additionally, it is advisable to consider reducing water losses in the distribution network for urban purposes, as the overall average of losses is currently reported around 23.1%, considering the entire NUTS II region, with several water managing entities reporting losses around or up to 50%.

Subsequently, the simulations include a win-win measure that consists of the implementation of techniques promoting greater water retention in the soil (e.g., direct seeding, mulching) and the creation of water retention landscapes (e.g., creating ponds, planting in valleys and berms). This can contribute to a longer maintenance of the balance between water supply and demand in NUTS II through transformative adaptation.

The usage of water for reuse (a no-regrets measure) can be implemented in a second phase, being also a viable solution, although its implementation is primarily directed towards urban or agricultural areas near urban clusters.

It is also crucial to ensure the success of the suggested adaptation actions by raising awareness and providing training to farmers. Farmer training should cover adaptive agricultural practices to help them cope with changing conditions, including the implementation of water management techniques, the introduction of drought-resistant crops, and the adjustment of planting and harvesting schedules. In this context, it is worth noting that the impacts of climate change will affect not only water availability but also agricultural productivity. Even if all plant water and nutrient needs are met, productivity losses will occur in scenarios with higher greenhouse gas emissions/concentrations over the century due to changes in plant phenology.

Adaptation in RH1 Minho e Lima

In economic terms, the projected impacts of climate change on water availability for RH1 could result in losses for the entire River Basin, averaging up to 85 thousand euros per year in RCP4.5 for the timeframe 2041-2070, and up 71 thousand euros per year for the period 2071-2100. Considering other scenarios, gains can vary, averaging up to 54 thousand euros (RCP2.6 period 2071-2100), while losses can exceed 230 thousand euros on average per year (RCP8.5 period 2071-2100).

In the River Basin, projections indicate a marginal decline in the average annual volume stored within the reservoirs. This decrease is expected to be around -2.1% under the RCP4.5 scenario, as outlined in Table 2.5. This reduction assumes greater significance under the RCP8.5 scenario, where it could potentially extend to -4% by the end of the century. Under RCP2.6 scenario, there's a projection of a slight reduction in average stored volumes, though it's deemed minor.

Table 2.5 – Projected changes in average annual volume stored in reservoirs in % for RH1, considering two future periods (anomaly) 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. The presented values refer to the ensemble median.

River Basins (RH1)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Reservoirs Availability	-1.2%	-2.1%	-2.6%	-1%	-1.8%	-4.2%

With the implementation of the above-mentioned adaptation measures for RH1, the identified economic impacts could be minimized in this river basin, and some benefits would be achieved. Table 2.6 shows the overall results for RH1 with the percentage point changes to the Water Exploitation Index Plus regarding the implementation of each of the following adaptation measures: improving irrigation efficiency, selection of crops better suited to climate change projections, and wastewater recycling and reuse.

Table 2.6 – Projected change in WEI+ (in percentage points) for RH1 are shown considering two future periods:2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. The presented anomalies refer to the ensemble median and consider the following factors: no adaptation, the improvement of irrigation efficiency, the selection of crops better suited to climate change projections, and wastewater recycling and reuse.

River Basins (RH1)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Climate change impacts (no adaptation)	+0.35 pp	+0.70 pp	+0.81 pp	+0.25 pp	+0.56 pp	+1.68 pp
Improving irrigation efficiency	+0.11 pp	+0.33 pp	+0.49 pp	+0.07 pp	+0.40 pp	+1.41 pp
Changing current irrigated crops	-0.33 pp	-0.19 pp	-0.02 pp	-0.42 pp	-0.25 pp	+0.23 pp
Wastewater for reuse	-0.18 pp	+0.05 pp	+0.20 pp	-0.25 pp	+0.06 pp	+1.09 pp

All the individually modelled measures contribute to benefiting the region by reducing the disparities between the projected and the scenario of no adaptation. Among these measures, changing current irrigated crops to others more adapted to the projected climate stands out as the most beneficial. It is noteworthy that this adaptation can neutralize the impacts of climate change on water balance and improve the current situation, except for RCP8.5 by the end of the century.

Since not all discussed measures were modelled, a prioritization of adaptation measures for RH1 is presented in Figure 2.8. The figure outlines the timeline for the full implementation of each measure aimed at mitigating the projected impacts of climate change. The proposed timeframe may be subject to change based on ongoing monitoring of the impacts of climate change, aiming to implement adaptive management over time.

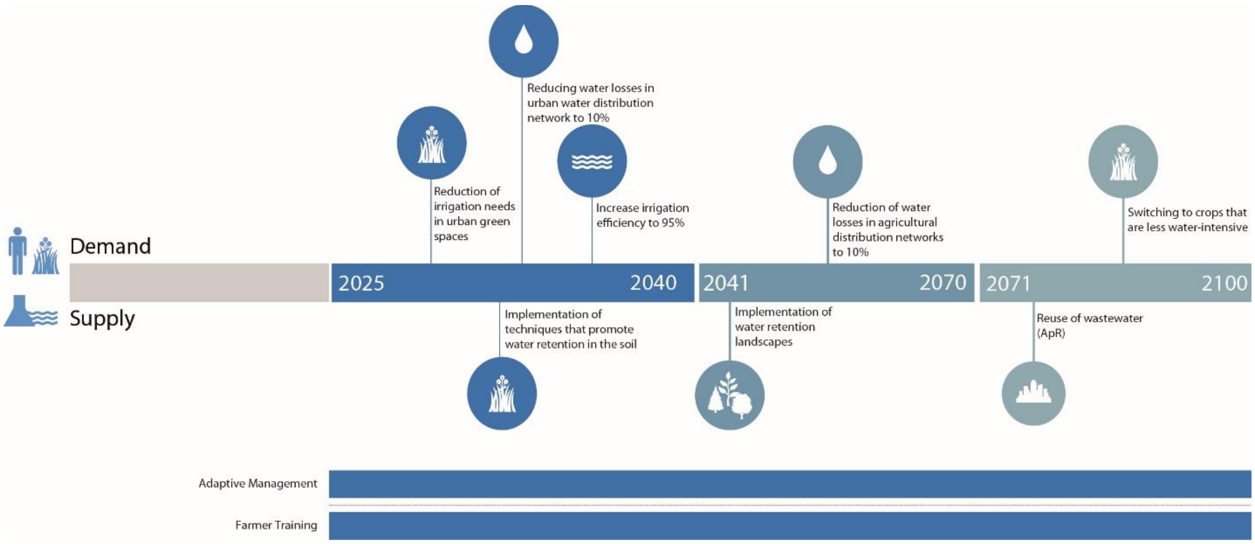


Figure 2.8 – Adaptation narrative for the water resources and agroforestry sectors in RH1 until 2100.

Adaptation in RH2 Cávado, Ave e Leça

In economic terms, the projected impacts of climate change on water availability for RH2 could result in losses for the entire River Basin, averaging up to 54 thousand euros per year in RCP4.5 for the timeframe 2041-2070, and up 21 thousand euros per year for the period 2071-2100. Considering other scenarios, gains can vary, averaging up to 13 thousand euros (RCP2.6 period 2071-2100), while losses can exceed 216 thousand euros on average per year (RCP8.5 period 2071-2100).

In the River Basin, projections indicate a marginal decline in the average annual volume stored within the reservoirs. This decrease is expected to be around -1% under the RCP4.5 scenario, as outlined in Table 2.7. This reduction assumes greater significance under the RCP8.5 scenario, where it could potentially extend to -3.9% by the end of the century. Under RCP2.6 scenario, there's a projection of a slight reduction in average stored volumes, though it's deemed insignificant.

Table 2.7 – Projected changes in average annual volume stored in reservoirs in % for RH2, considering two future periods (anomaly) 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. The presented values refer to the ensemble median.

River Basins (RH2)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Reservoirs Availability	-0.6%	-1.2%	-2.2%	-0.7%	-0.8%	-3.9%

With the implementation of the above-mentioned adaptation measures for RH2, the identified economic impacts could be minimized in this river basin, and some benefits would be achieved. Table 2.8 shows the overall results for RH2 with the percentual changes to the Water Exploitation Index Plus with the implementation of each of the following adaptation measures: improving irrigation efficiency, selection of crops better suited to climate change projections, and wastewater recycling and reuse.

Table 2.8 – Projected change in WEI+ (in percentage points) for RH2 are shown considering two future periods:2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. The presented anomalies refer to the ensemble median and consider the following factors: no adaptation, the improvement of irrigation efficiency, the selection of crops better suited to climate change projections, and wastewater recycling and reuse.

River Basins (RH2)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Climate change impacts (no adaptation)	+0.58 pp	+1.31 pp	+1.43 pp	+0.45 pp	+0.95 pp	+3.99 pp
Improving irrigation efficiency	+0.13 pp	+0.72 pp	+0.99 pp	+0.02 pp	+0.71 pp	+3.43 pp
Changing current irrigated crops	-0.60 pp	-0.33 pp	+0.05 pp	-0.73 pp	-0.64 pp	+0.70 pp
Wastewater for reuse	-0.89 pp	-0.42 pp	-0.16 pp	-1.03 pp	-0.35 pp	+1.49 pp

All of the individually modelled measures contribute to benefiting the region by reducing the disparities between the projected and the scenario of no adaptation. Among these measures, changing current irrigated crops to others more adapted to the projected climate or wastewater recycling and reuse stand out as the most beneficial. It is noteworthy that these adaptation measures can neutralize the impacts of climate change on water balance and improve the current situation, except for RCP8.5.

Since not all discussed measures were modelled, the prioritization of all adaptation measures for RH2 is presented in Figure 2.9. The figure outlines the timeline for the full implementation of each measure aimed at mitigating the projected impacts of climate change. The proposed timeframe may be subject to change based on ongoing monitoring of the impacts of climate change, aiming to implement adaptive management over time.

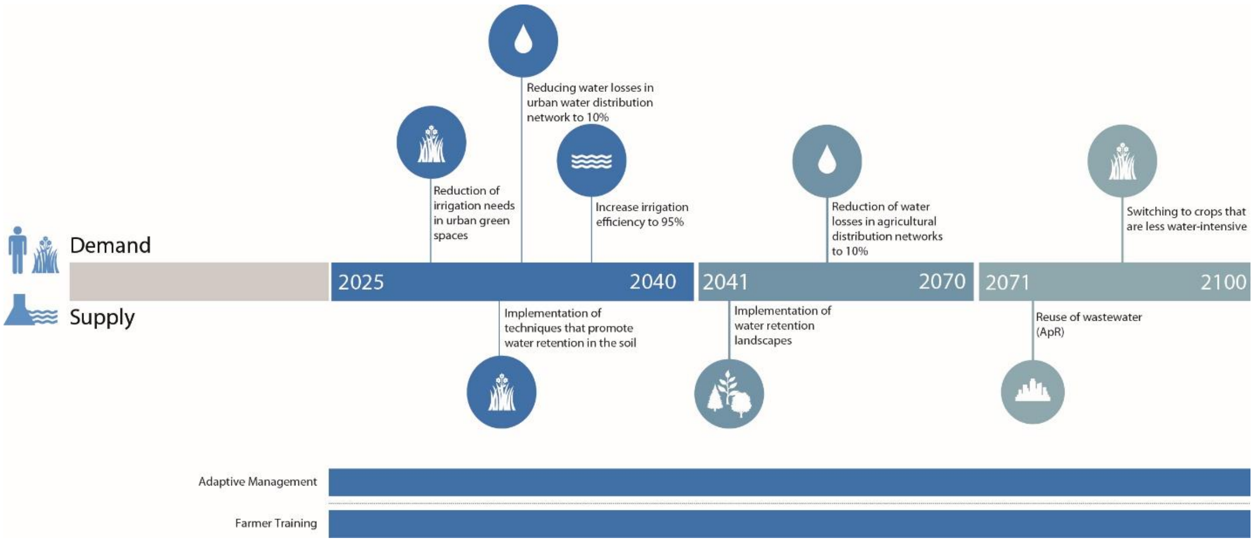


Figure 2.9 – Adaptation narrative for the water resources and agroforestry sectors in RH2 until 2100.

Adaptation in RH3 Douro

In economic terms, the projected impacts of climate change on water availability for RH3 could result in losses for the entire River Basin, averaging up to 70 thousand euros per year in RCP4.5 for the timeframe 2041-2070, with residual gains into the period 2071-2100. Considering other scenarios, gains can vary, averaging up to 38 thousand euros (RCP2.6 period 2041-2070), while losses can exceed 180 thousand euros on average per year (RCP8.5 period 2071-2100).

In the River Basin, projections indicate a marginal decline in the average annual volume stored within the reservoirs. This decrease is expected to be around -0.5% under the RCP4.5 scenario, as outlined in Table 2.9. However, despite projecting a decrease in some scenarios, the values obtained are not significant, leading to the assumption that the situation will remain stable throughout the century.

Table 2.9 – Projected changes in average annual volume stored in reservoirs in % for RH3, considering two future periods (anomaly) 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. The presented values refer to the ensemble median.

River Basins (RH3)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Reservoirs Availability	-0.2%	-0.6%	-0.6%	-0.1%	-0.5%	-1.1%

With the implementation of the above-mentioned adaptation measures for RH3, the identified economic impacts could be minimized in this river basin, and some benefits would be achieved. Table 2.10 shows the overall results for RH3 with the percentual changes to the Water Exploitation Index Plus with the implementation of each of the following adaptation measures: reducing system water loss and leakages, improving irrigation efficiency, selection of crops better suited to climate change projections, and wastewater recycling and reuse.

Table 2.10 – Projected change in WEI+ (in percentage points) for RH3 are shown considering two future periods: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. The presented anomalies refer to the ensemble median and consider the following factors: no adaptation, the reduction of system water loss and leakages, the improvement of irrigation efficiency, the selection of crops better suited to climate change projections, and wastewater recycling and reuse.

River Basins (RH3)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Climate change impacts (no adaptation)	+0.05 pp	+0.47 pp	+0.52 pp	+0.04 pp	+0.45 pp	+2.42 pp
Reducing system water loss and leakages	+0.01 pp	+0.45 pp	+0.50 pp	+0.02 pp	+0.42 pp	+2.36 pp
Improving irrigation efficiency (entails reducing system water loss and leakages simultaneously)	-0.22 pp	+0.36 pp	+0.40 pp	-0.13 pp	+0.22 pp	+2.01 pp
Changing current irrigated crops (entails reducing system water loss and leakages simultaneously)	-0.42 pp	+0.20 pp	+0.19 pp	-0.56 pp	-0.09 pp	+1.38 pp
Wastewater for reuse (entails reducing system water loss and leakages simultaneously)	-0.91 pp	-0.12 pp	-0.07 pp	-1.00 pp	-0.40 pp	+1.00 pp

All of the individually modelled measures bring some benefit to the region by reducing the differences between the projected and the historical WEI+. The measure that brings the most benefits, among those that were modelled, involves wastewater recycling and reuse in combination with reducing system water loss and leakages on hydro-agricultural developments. It is noteworthy that this measure can neutralize the impacts of climate changes on water balance or even improve the current situation, except for RCP8.5.

Since not all discussed measures were modelled, the prioritization of all adaptation measures for RH3 is presented in Figure 2.10. The figure outlines the timeline for the full implementation of each measure aimed at mitigating the projected impacts of climate change. The proposed timeframe may be subject to change based on ongoing monitoring of the impacts of climate change, aiming to implement adaptive management over time.

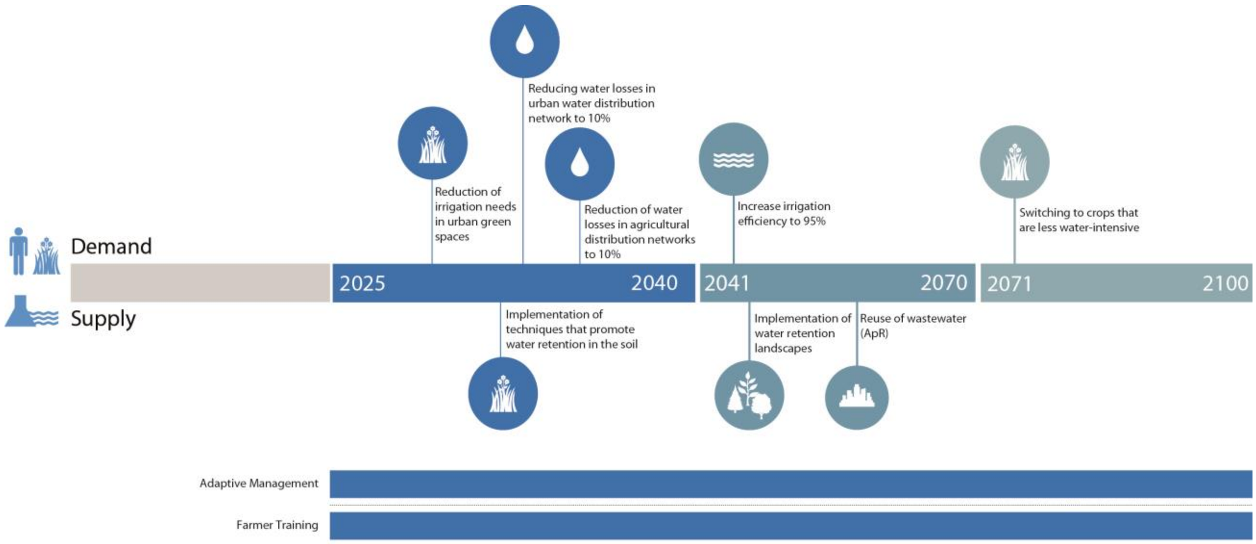


Figure 2.10 – Adaptation narrative for the water resources and agroforestry sectors in RH3 until 2100.

2.1.3. Coastal flooding

The Norte region is the northernmost NUTSII sub-section of Portugal Mainland territory, showing quite diverse coastal environments, from natural to highly-anthropizes ones (Figure 2.11). Most of these environments (particularly the latter) are shown to be vulnerable to the impacts of rising sea levels and changes in wave climate patterns (the reader is referred to the WP4.5/6 dynamic modelling report). The Norte region encompasses a coastal stretch of about 115 km in length. It is dominated by low rocky beaches and cliffs, intersected by low sandy beaches, often backed by dunar systems, such as in Moledo, Ofir, Madalena and Aguda. The inland waters of the Douro and Cávado rivers estuaries face important population centers, namely Porto, Vila Nova de Gaia and Esposende. Sandy beaches with adherent structures can be found (*e.g.*, Vila do Conde), and urban beaches are often present (*e.g.*, Póvoa de Varzim, Matosinhos, Porto, Espinho).

Figure 2.11 – The Norte NUTSII region, depicting the most relevant locations in terms of projected coastal vulnerability.

The vulnerability assessment carried for the Norte region revealed that moderate-to-high vulnerability is projected for urbanized areas by the middle of the 21st century, even under the moderate concentrations' RCP4.5 scenario, namely in Viana do Castelo, Esposende and along the Madalena-Valadares coastal stretch (Figure 2.12). The coastlines facing inland waters (restricted to estuaries in this coastal section) are projected to be generally more threatened, showing high vulnerability to the projected changes in total water levels[16], due to the extensive low-lying areas on both shores of the rivers, often used for agricultural, industrial, leisure or even habitational purposes. These areas are consistently threatened by extreme coastal flooding conditions associated to return periods as frequent as every 4 years, for both scenarios, despite small variations in the extension of the low, moderate and high vulnerability categories.

Considering the Norte region as a whole, and for the three classes of vulnerability adopted through the Coastal Vulnerability Index (CVI; low, medium and high, associated to the 100-, 25- and 4-year total water level return values) projections revealed 8.0-10.3 km² of vulnerable ocean-facing coastlines (beaches), and 12.7-14.3 km² of vulnerable coastlines facing inland waters (Minho, Lima, Neiva, Cávado and Ave rivers estuaries; Table 2.11), depending on the future period and scenario. Departing from the intermediate RCP4.5 scenario, on a trajectory closer to the RCP8.5, an increase up to 1.4 km² in the vulnerable areas of the Norte region is projected by 2100.

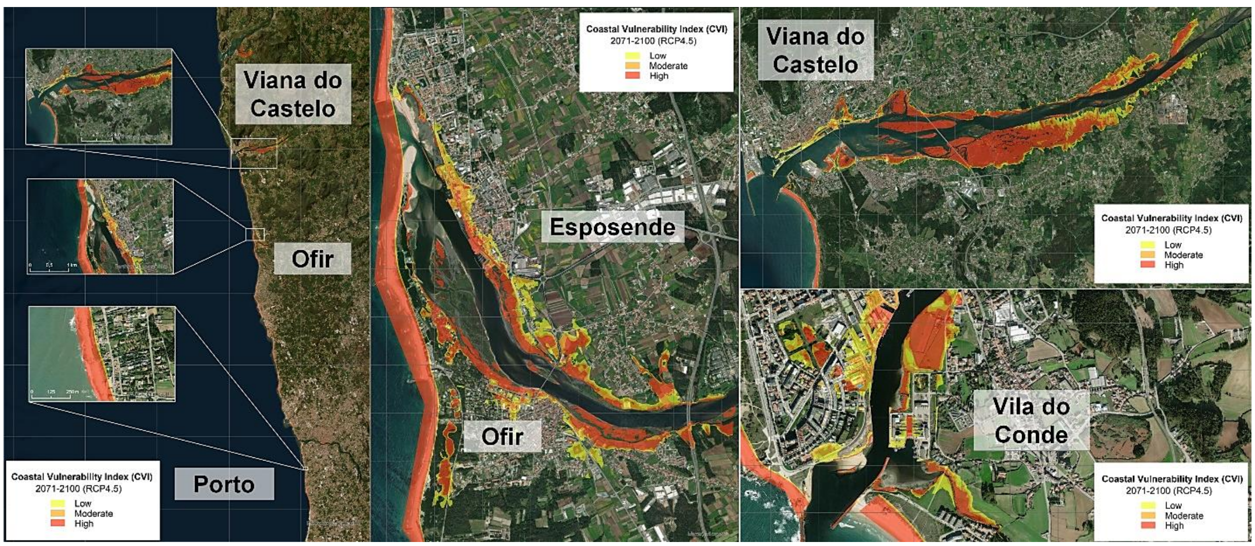


Figure 2.12 – Projected vulnerable areas along the Norte region by the end of the 21st century (2071-2100) under RCP4.5, with focus on three different stretches of coast, near Ofir, Viana do Castelo and Vila do Conde, along the Lima, Cávado and Ave River mouths, respectively. The CVI is inversely related to the TWL 4-, 25- and 100-years return period values (*e.g.*, a high CVI is given to coastal areas projected to become flooded under a 4-year RP TWL).

[16] The total water level (TWL) is given by the sum of the sea level rise (SLR), tide and storm surge components. For the ocean-facing coastlines, the run-up associated with a 99th percentile energy wave event is also considered.

Table 2.11 – Area (in km²) of the vulnerable coastal stretches in the Norte region (grouped for the three classes of vulnerability), by the end of the 2041-2070 and 2071-2100 future periods, under both RCP4.5 and RCP8.5 scenarios.

Vulnerable coastal areas (km²)				
Norte region	2041-2070		2071-2100	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Ocean-facing	8.0	8.2	9.6	10.3
Inland	12.7	12.2	13.6	14.3
Total	20.7	20.4	23.2	24.6

Considering the diverse coastal environments in the area, a single common adaptation narrative is not feasible. Instead, narratives are built for the multiple coastal typologies of the Norte region. Therefore, Figure 2.17 depicts, schematically, the proposed adaptation pathways along the five identified coastal environments. For each one, different pathways are shown, spanning from the present time until the end of the 21st century, and varying due to: (1) each coastal environment's expected response to changes in total water levels and wave characteristics (if facing the ocean), (2) the different possibilities in terms of adaptation strategies, and (3) any site-specific adaptation effort that was already carried in the recent past.

Sandy beaches with adherent structures
(e.g., Vila do Conde)

Low-lying sandy beaches
(e.g., Esposende – Praia da Ramalha)
Source: www.playocean.net

Pocket beaches and rocky cliffs
(e.g., Vila Chã – Praia de São Paio)

Urban beaches
(e.g., Matosinhos)

Inland waters
(e.g., Cávado River estuary)

Figure 2.13 – Different coastal environments in the Norte NUTSII region. Specific adaptation pathways are built for each environment in Figure 2.16.

Overall, in accordance with the current national adaptation plan (Pinto et al., 2020), artificial beach nourishment corresponds to a transversal measure, to be applied along different coastal environments of the Norte region, except for sandy beaches with increased sedimentary stocks (as well as natural protection structures, such as dunes; Figure 2.13), and the coastlines facing inland waters (estuaries; Figure 2.13 and Figure 2.15). Note, nevertheless, that such interventions are usually quite localized and may vary greatly in terms of frequency and intensity even within the same coastal environment. Across the Norte region, artificial beach nourishment has been pursued as a local solution to contain the observed erosion trends at Moledo, Vila Praia de Âncora, Ofir, Póvoa de Varzim, Vila do Conde, Leixões, Matosinhos, among others. These interventions are, however, greatly dependent on the beaches' relevance for tourism as well as the need to protect local populations and infrastructures, which dictates that other areas with similar coastal environments and vulnerability levels might not be eligible for this measure. Nevertheless, considering the availability of dredged sediments from Leixões, Viana do Castelo and Vila Praia de Âncora harbors, artificial nourishment is considered as the most viable adaptation measure for the urban and sandy beaches with adherent structures along the Norte region, at least until the beginning of the 2040s. Where applicable, the demolition of exposed illegal or non-essential structures should also be a priority within this timeframe (Figure 2.17).

The accommodation of the adherent structures (such as seawalls, tidal dykes and harbour structures; Figure 2.15) is considered a viable option to protect the urbanized areas inland. Although it may be currently considered as a secondary measure, it is projected to become increasingly relevant towards the middle of the 21st century. Bear in mind, for example, that the existing seawalls at Vila Praia de Âncora, Póvoa de Varzim, Mindelo and Vila Nova de Gaia were not able to sustain the effects of the Hercules storm (in January 2014), with several overtopping reports. Given the future projected increase in total waters levels (mostly due to SLR), existing adherent structures may require additional levels of protection. Due to long-term shoreline retreat, not only is artificial beach nourishment projected to become progressively more ineffective (given the permanent flooding of the pre-existing beaches in the base of the adherent structures), but also are the low-lying areas surrounding the inland waters of the Minho, Lima, Neiva, Cávado and Ave rivers estuaries projected to become increasingly threatened.

The required topographic height (relative to the National Vertical Datum CASCAIS1938) for the coastal protection structures to withstand the future projected extreme coastal events[17] is set at 8.23 m, under the intermediate RCP4.5 scenario (Figure 2.14), for the analysis conducted at Ofir. Excluding wave action, the required height for inland waters coastal protection structures is set at 3.45 m, in order to sustain a 100-year return period event by the end of the 21st century. Departing from the RCP4.5, on a trajectory closer to the RCP8.5, while an increase of up to 0.10 m (3.45 m → 3.55 m) is expected for the structures' heights facing inland waters, for the ocean-facing ones, the value is projected to be lowered by 0.33 m (8.23 m → 7.90 m). These values should be considered as references to all ocean-facing and inland waters coastlines of the Norte region. Note, nevertheless, that coastal stretches with steeper slopes, usually present at highly anthropized ocean-facing segments (*e.g.*, Viana do Castelo, Esposende, Aguçadoura, Póvoa de Varzim, Vila do Conde, Matosinhos, Espinho), may expect higher run-up values.

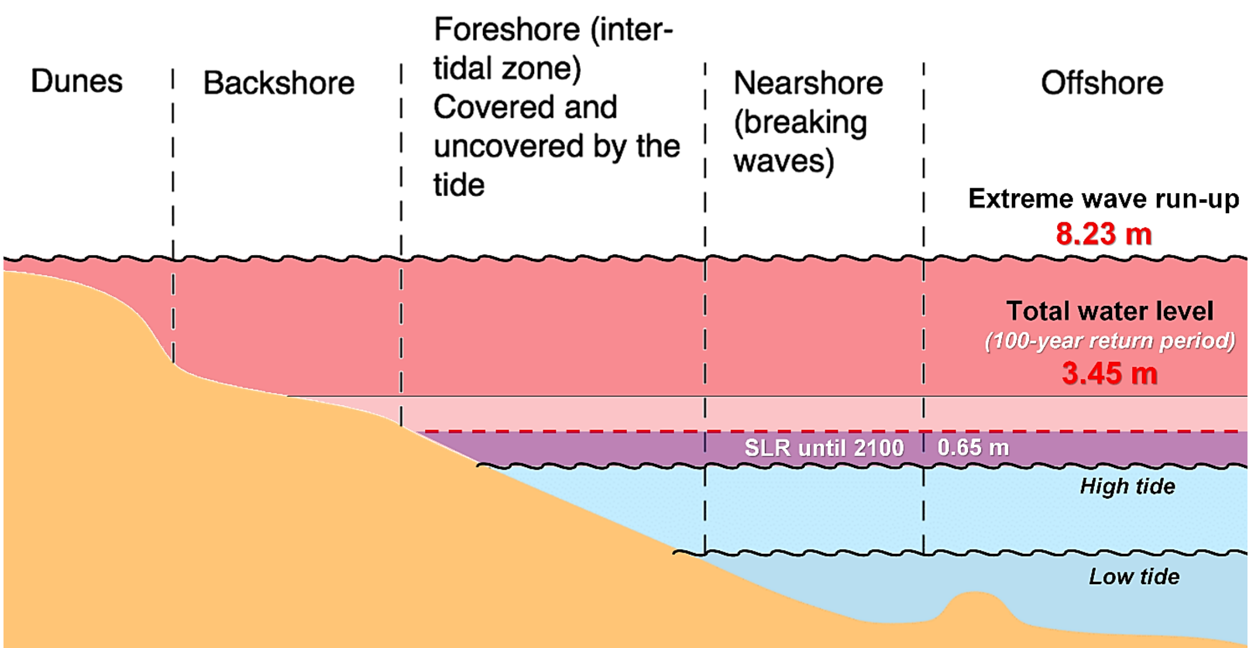


Figure 2.14 – Schematic depiction of how changes in total water levels and run-up may lead to coastal flooding. Note that while for inland waters the maximum coastal flooding topographic height is projected to be set at 3.45 m, for ocean-facing coastlines the value is projected to be set at 8.23 m (values for the RCP4.5 scenario by the end of the 21st century).

[17] Considering a 99th percentile wave energy event over a 25-year TWL return value.

While accommodation may still be a viable option towards the end of the 21st century, planned relocation actions (Figure 2.15) should become the most cost-effective way to deal with continuously rising sea levels and extreme coastal flooding along most of the Norte coastlines, as soon as by the mid-21st century, especially for densely urbanized stretches (Figure 2.17; Table 2.12). Exceptions are the rocky cliffs and pocket beaches, for which the natural terrain configuration is enough to protect local populations from changes in the sea levels. Nevertheless, without continuous artificial nourishment interventions (which should be considered as a local option – and not a generalized one – if the economic or natural value of the beach justifies it), the pocketed beaches are projected to disappear or be extensively reduced towards the end of the 21st century.

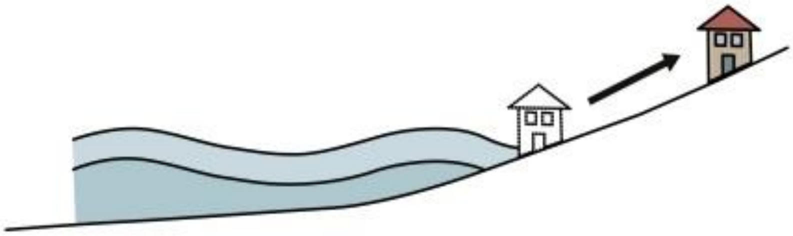
Artificial nourishment

Accommodation of adherent structures

Source: www.playocean.net

Nature-based solutions for dune rehabilitation and preservation

Improved warning systems



Planned relocation

Figure 2.15 – Examples of adaptation measures to be applied in the Norte region, and present in the proposed adaptation pathways of Figure 2.17.

The demographic and cost-benefit analysis performed for the Norte region is expressed in Table 2.12. Under the RCP4.5 scenario, more than 6200 habitants (according to the CENSOS2021) are projected to become vulnerable[18] until the end of the 21st century, from over 2300 vulnerable buildings. Total inaction costs due to patrimonial losses (without adaptation measures; TIC) top at over 683 and 985 million € by 2070 and 2100, respectively, for all coastlines (both inland and ocean-facing ones). The portion of the TIC associated to each coastal municipality of the Norte region is depicted in Figure 2.16. Total adaptation costs (TAC), calculated exclusively for ocean-facing coastlines, surpass the 534 and 841 million € marks, exceeding the TIC for the same coastlines (370 and 548 million €). Therefore, while fostering adaptation strategies is

[18] *i.e.*, exposed to at least a 100-year return period flooding event.

overall recommended for the Norte region, the advantages of reducing the populations' exposure to coastal hazards are significant, and relocation efforts are suggested for the most urbanized ocean-facing coastal stretches (Figure 2.17), due to the unbalanced cost-benefit ratio of the remaining adaptation measures in these coastal environments.

Table 2.12 – Demographic (number of vulnerable residents and buildings projected as vulnerable, *i.e.*, under CVI) and economic cost analysis considering the total inaction costs (TIC) and the total adaptation costs (TAC) in the Norte region, by 2070 (end of the 2041-2070 period) and 2100 (end of the 2070-2100 period), under the RCP4.5 scenario.

Norte region (RCP4.5 scenario)	2070	2100
Number of residents under CVI	4529	6267
Number of buildings under CVI	1777	2379
TIC from 2024 onwards – maximum (M€)	683.4	985.1
TIC from 2024 onwards – maximum for ocean-facing coastlines (M€)	370.0	548.0
TAC from 2024 onwards for ocean-facing coastlines (M€)	534.3	840.8
Annualized maximum TIC (M€/year)	14.5	12.8
Annualized maximum TIC for ocean-facing coastlines (M€)	7.9	7.1
Annualized TAC for ocean-facing coastlines (M€/year)	11.4	10.9

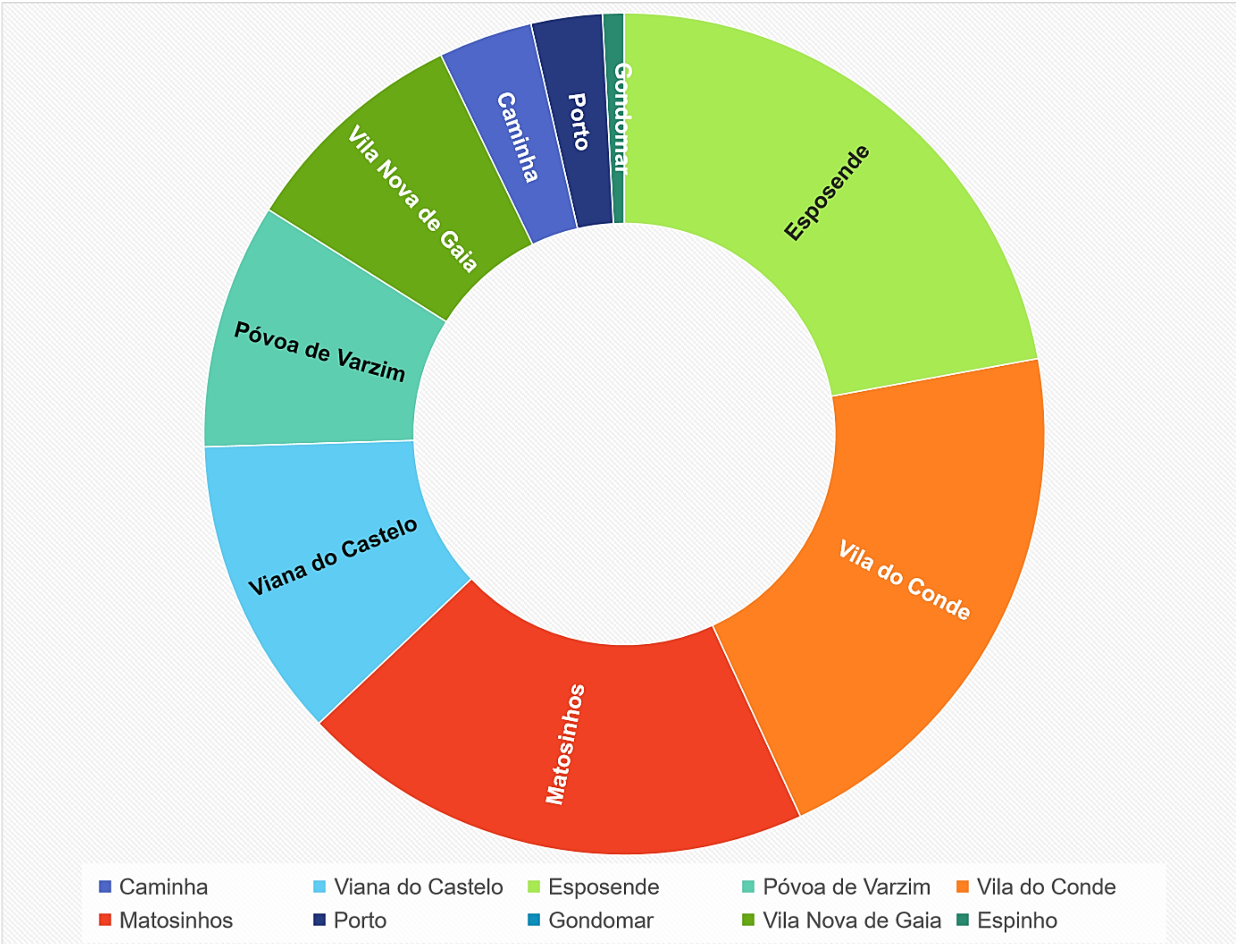


Figure 2.16 – Portion of the TIC (until 2100 under RCP4.5) associated to each coastal municipality of the Norte region.

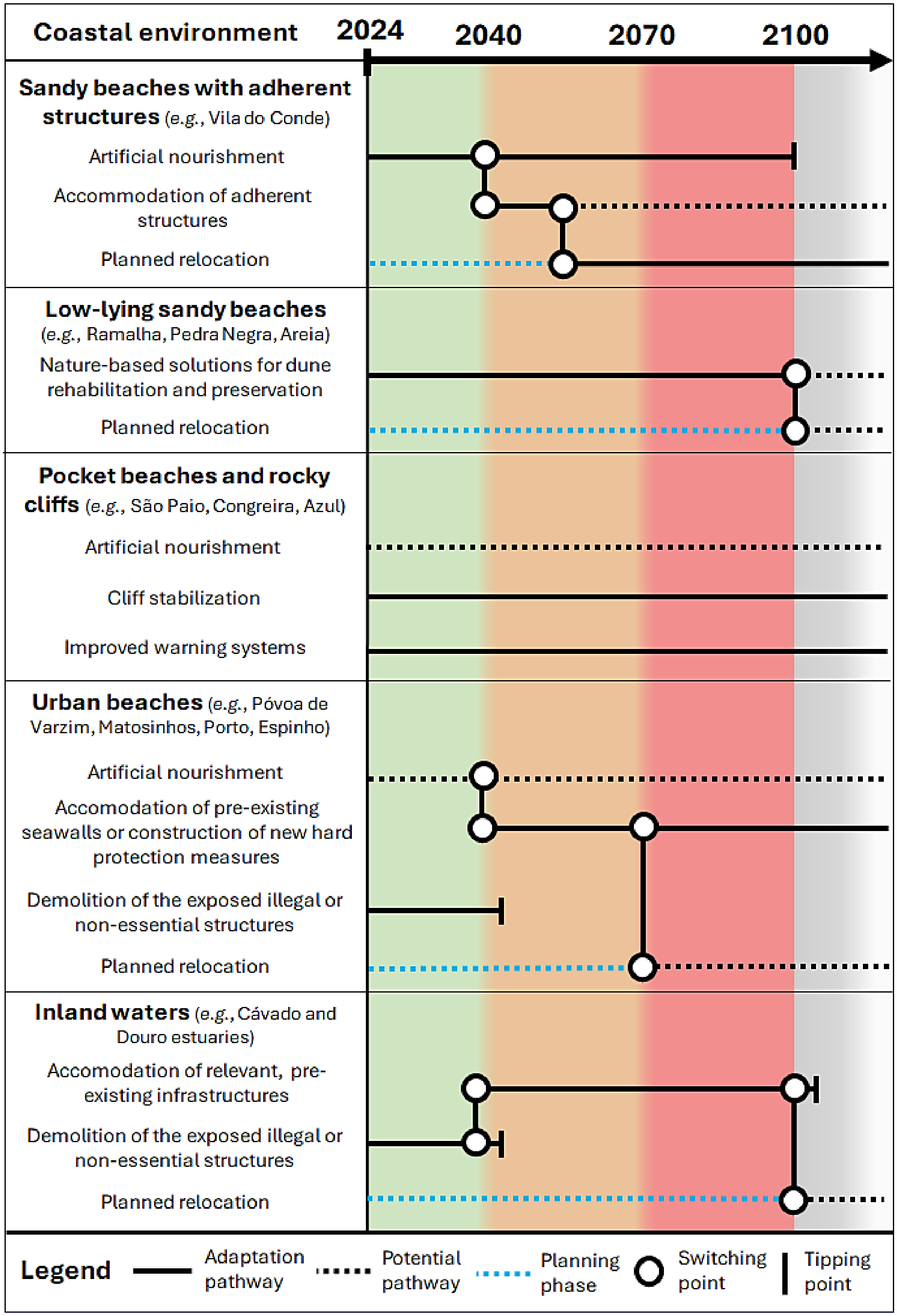


Figure 2.17 – Proposed adaptation pathways along the five identified environments present in the Norte NUTSII region, departing from the year 2024, and spanning until the end of the 21st century. The pathways in full correspond to the most viable adaptation strategy for each coastal environment.

2.1.4. Forest fires

The northern region of Portugal (Figure 2.18), including areas such as Picões (near the Douro International Natural Park, has historically grappled with devastating wildfires, with the fires of 2013 standing out as a poignant example of the region's vulnerability to such events. These wildfires, which ravaged vast swaths of forest and countryside, left a profound impact on the landscape, communities, and economy of the region. The fires of 2013 serve as a stark reminder of the significant challenges posed by wildfires in northern Portugal, highlighting the urgent need for effective adaptation strategies to mitigate future risks. The fires of 2013 were exacerbated by a combination of factors, including prolonged periods of hot and dry weather, strong winds, and the presence of highly combustible vegetation. These conditions created a perfect setting for fire ignition and spread, leading to widespread devastation and loss of life. The events of 2013 underscore the critical role of meteorological conditions in shaping fire danger, with extreme weather events such as heatwaves and droughts increasing the susceptibility of the region to wildfires. In addition to meteorological factors, human activities and land use practices also played a significant role in fuelling the fires of 2013. Factors such as land abandonment, inadequate forest management and illegal burning practices contributed to the severity and extent of the wildfires, highlighting the complex interplay between human and environmental factors in shaping fire regimes.

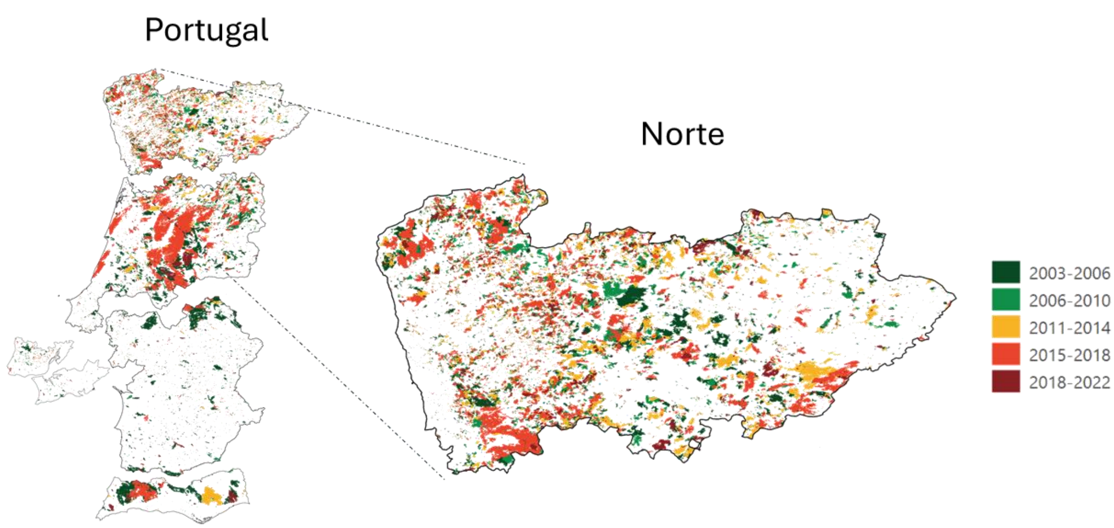


Figure 2.18 – Highlight of Norte burned area, with the colours representing the period where the last occurrence took place.

To comprehend the variable distribution and damage caused by wildfires in the northern region of Portugal, it is crucial to consider these multifaceted factors. By understanding the interaction between meteorological conditions, vegetation characteristics, and human activities, stakeholders can devise practical adaptation options to mitigate future wildfire risks. Through a combination of forest management practices, land use planning, fire prevention measures, and community engagement, the region can build resilience to wildfires and ensure the long-term sustainability of its natural ecosystems and communities.

Hence, the future meteorological danger was assessed by taking advantage of the enhanced Fire Weather Index (FWIe)[19]. It is foreseen an increase in the number of extreme fire danger days, at short-term varying between + 8 to +22 days, that can reach +40 days at the end of the century under RCP8.5, an increase of almost 4 times the 15-days mark observed in the present climate (Table 2.13). For the RCP4.5 the additional number of days with extreme fire danger is +16 and +19 for the mid- and end-century periods, respectively.

Table 2.13 – Additional number of days per extended summer (June to September) with extreme fire danger for different emission scenarios compared to the present climate.

Norte	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Additional days (present climate = 15 days)	+8	+16	+22	+7	+19	+40

Importantly, the return periods of burned areas reaching 50,000 ha, which occurred once every 3 years in the historical period are expected to occur much more frequently in the future, occurring once every year and a third for RCP4.5 (almost 2 years for RCP2.6 and yearly for RCP8.5) if no adaptation measures are pursued (Figure 2.19).

[19] The enhanced FWI is a meteorological fire danger index that combines an atmospheric instability parameter.

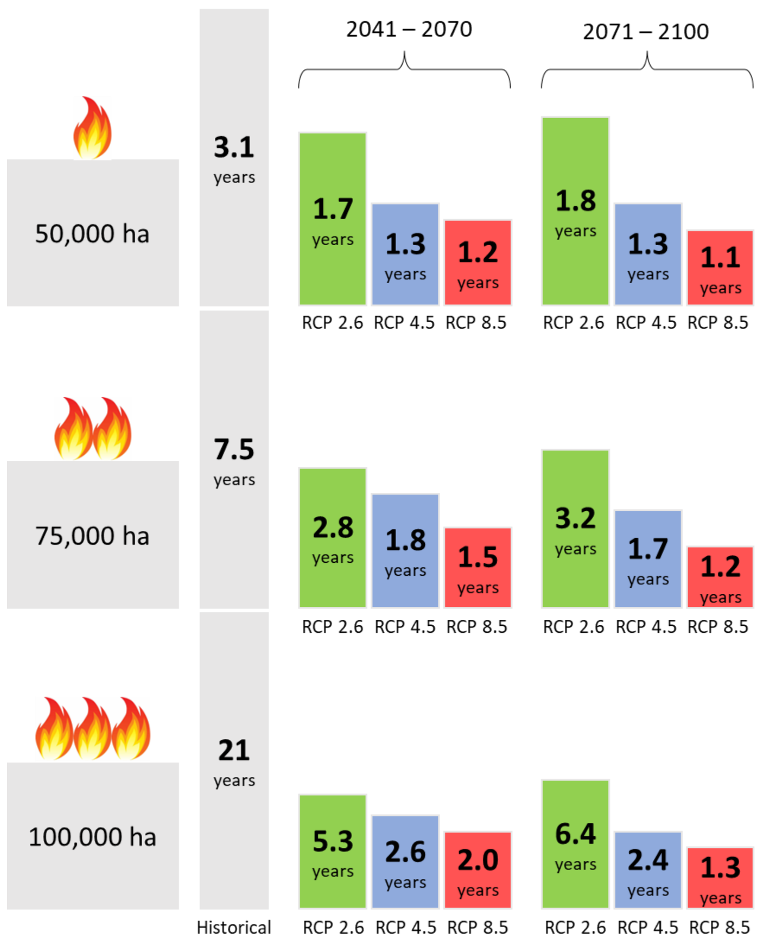


Figure 2.19 – Return periods of three large burned area thresholds, taking into account the no adaptation pathway for the Norte region.

In the Norte region of Portugal, the implementation of adaptation strategies is critical to mitigate the escalating threat of forest fires and their associated costs. Recognizing the urgency of the situation, a multifaceted approach is being devised, drawing upon insights from various fields of expertise and tailored to the unique challenges faced by the region. Efforts are underway to minimize the extent of burned areas and enhance post-fire land management practices. By reducing the annual burned area and strategically reforesting with resilient species, the region aims to not only mitigate fire risks but also bolster carbon sequestration and ecosystem resilience. Furthermore, educational initiatives targeting individuals of all ages are being implemented to foster a culture of fire prevention and safety, with the goal of reducing fire ignitions by up to 50%. Similarly, in the Norte region, which encompasses diverse landscapes and ecosystems, adaptation strategies focus on reducing the frequency and severity of wildfires through targeted interventions. By leveraging meteorological forecasts and early warning systems, authorities can prioritize resources and respond swiftly to extreme fire danger days, thereby reducing the number of very energetic fires and associated costs. This focused approach could lead to significant cost savings, with each avoided large wildfire translating into millions of euros saved. Overall, the cost of adaptation measures is offset by the substantial savings achieved through proactive wildfire prevention efforts. By investing in forest management practices, educational campaigns, and early warning systems, the Norte region aims to build resilience to the growing threat of forest fires, ensuring the long-term sustainability of its natural environments and communities.

When considering the 2013 fire season, where ~15,000 ha burned in the Norte and losses were estimated at 13 million euros, it seems crucial that extreme meteorological danger days are expected to be about four times more, with almost half of the summer in such condition. The probability of having a wildfire like the one from Picões in the future may double under RCP4.5 depending on the energy that is released. In the current climate context, assuming similar losses per ha, the cumulative financial toll of forest fires over the past 20 years stands at around 869 million euros, i.e., about 43 million euros/year.

From the probabilistic model developed in the context of RNA2100, it is possible to estimate that the likelihood of having forest fires of similar intensity as the 2013 Picões event can be near 2 times the historical frequency, in agreement with the probability of exceedance of a given fire radiative power under the RCP4.5. Without proactive adaptation measures, the projected losses (Table 2.14) could escalate to nearly 83 million euros/year under RCP4.5 (almost doubling the 43 million euros/year mark).

Table 2.14 – Projected losses without implementing adaptation measures, in million euro/year for Norte region.

Norte (No adaptation)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Losses (million euro/year)	80.4	82.6	89.1	64.1	82.6	112.9

In regions such as the Parque Natural do Douro Internacional, the preservation of its unique and diverse forests and ecosystems is of paramount importance. Adaptation strategies play a crucial role in safeguarding these valuable ecosystems and mitigating the escalating threat of forest fires. Given the ecological significance of this region forests, adaptation measures aim to minimize the extent of burned areas and enhance post-fire land management practices. Through strategic reforestation efforts with species resilient to fire and conducive to carbon sequestration, the region aims to not only mitigate fire risks but also bolster biodiversity and ecosystem resilience. Moreover, implementing forest management practices that optimize productivity and sustainability are essential to maintaining the health and vitality of these forests.

These practices may include selective thinning, prescribed burning, and the promotion of mixed species stands to enhance ecosystem resilience and reduce the vulnerability of forests to wildfire. In addition to proactive forest management, educational initiatives targeting residents, visitors, and stakeholders are instrumental in fostering a culture of fire prevention and safety. By raising awareness about the ecological importance of the Douro region and the risks posed by wildfires, communities can become active participants in wildfire prevention efforts. Moreover, empowering local communities with the knowledge and resources to implement fire prevention measures on a grassroots level can significantly reduce fire ignitions and the severity of wildfires. Furthermore, leveraging advances in meteorological forecasting and early warning systems enables authorities to prioritize resources and respond swiftly to extreme fire danger days. By implementing targeted interventions on days with adverse weather conditions, such as increased patrols, enhanced surveillance, and coordinated firefighting efforts, the region can reduce the frequency and severity of wildfires, thereby safeguarding its forests and natural heritage. Overall, adaptation strategies serve as a crucial asset in preserving the forests of Parque Natural do Douro Internacional, ensuring their resilience to the growing threat of forest fires, and securing the long-term sustainability of the region's natural ecosystems and communities.

By integrating insights from forest management, ecology, meteorology and education, communities can build resilience to the growing threat of forest fires and ensure the long-term sustainability of their natural environment and way of life. These insights can be put in place under the three types of strategies that were assessed. One focused only on awareness measures, other on awareness and coercive measures, and the last only on coercive measures. Awareness measures cover initiatives such as continuous education and capacitation of the society. On the other hand, coercive measures encompass actions such as targeted fines. These adaptation measures aim to reduce ignitions and the costs related to large wildfires. For example, Figure 2.20 shows the projected losses without adaptation (black bar) and with implementation of adaptation measures (blue, green, and orange bars), in million euros/year for Norte. Focusing on RCP4.5, the 43 million euros/year mean value may reach 83 million euros/year under climate change, which means an increment of 40 million euros/year.

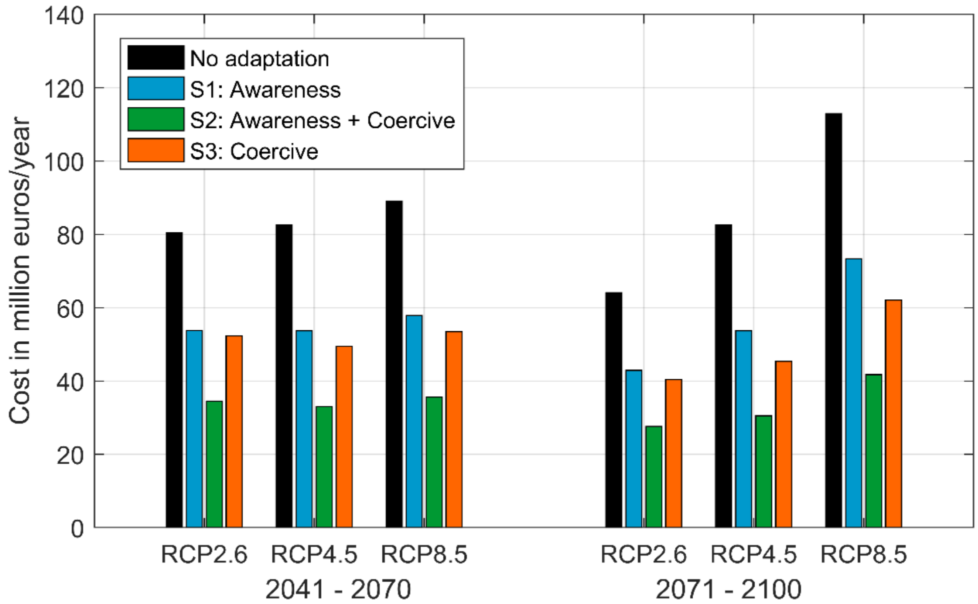


Figure 2.20 – Projected cost of no adaptation (black bar) and cost with implementation of adaptation strategies of Awareness (blue bars), Awareness + Coercive (green bars), and Coercive (orange bars), in million euros/year for Norte, under RCP2.6, RCP4.5, and RCP8.5 for the middle of the century (2041 – 2070; left) and the end of the century (2071 – 2100; right).

With a strategy focused on awareness, it is possible to reduce the losses to about 53 million euros/year. It is however important to note that with the advancement of time, climate change will severely impact the number of days in extreme danger, and consequently coercive strategies to reduce the number of ignitions and consequently burned area may be used. These strategies can represent savings of 30 million euros/year. However, it is essential to note that a pathway focused on both awareness and coercive strategies brings better results, to about 30 million euros/year, representing savings of the order of around 50 million euros/year to the no adaptation pathway. Figure 2.21 shows the adaptation pathway for Norte focused on RCP4.5. Several adaptation and mitigation strategies were already implemented and are expected to continue being implemented in the coming years. Awareness strategies should be first implemented to alert and educate society to the perils of climate change and its impact on forest fires. Eventually, in the most dangerous periods, coercive strategies should be implemented. However, with the increase in global warming, a mix between awareness and coercive continuous strategies must be implemented to prevent tragedies such as the 2013 Picões fire to become the new normal.

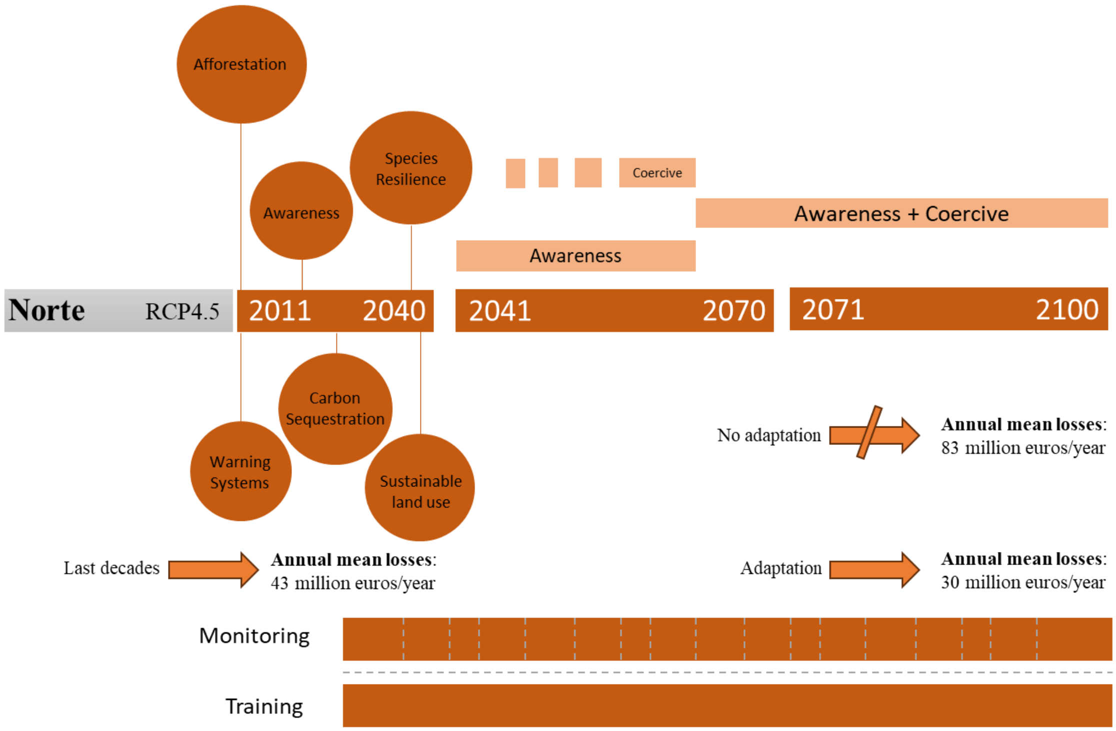


Figure 2.21 – Adaptation narrative for forest fires sector until 2100 for Norte under RCP4.5.

2.2. Centro

2.2.1. Climate projections

The Centro region is projected to experience more significant warming compared to the global mean. Projections indicate a more pronounced warming in summer than in winter across all climate scenarios. In the RCP4.5 scenario, the Centro region is projected to undergo a temperature rise of 1.9 – 2.6 ºC (Figure 2.22 and Table 2.15). Even under the RCP2.6 scenario, an increase in annual temperature of 1.4 ºC is expected during the 21st century. Under the RCP8.5 scenario, increases of +4.3 ºC and +4.7 ºC are foreseen by the end of the 21st century, respectively, for maximum and minimum temperatures.

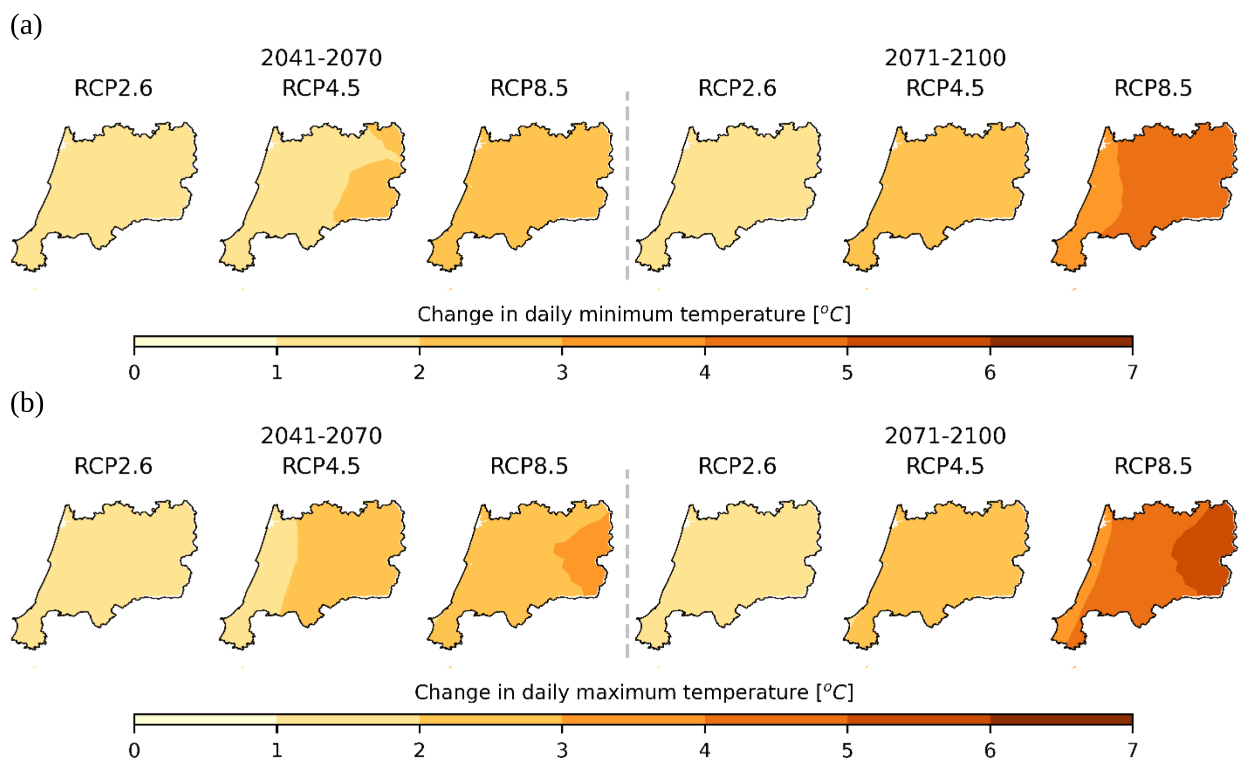


Figure 2.22 – Future projected changes in daily (a) minimum and (b) maximum temperature (ºC) for the Centro NUTS II region.

Table 2.15 – Climatological annual mean daily minimum (Tn) and maximum (Tx) temperature (ºC) for the reference period (Historical – 1971-2000); and, future projected changes in daily minimum and maximum temperature (ºC) for the Centro NUTS II region.

Centro	1971-2000 Historical	Differences	2041-2070			2071-2100		
			RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
T_n (°C)	8.4	ΔT_n (°C)	1.4	1.9	2.5	1.4	2.4	4.3
T_x (°C)	18.7	ΔT_x (°C)	1.5	2.1	2.7	1.4	2.6	4.7

Changes in precipitation are greatly dependent on the season and the future emission scenario. Future projections suggest a decline in mean precipitation across the 21st century under RCP4.5 and RCP8.5, and a small increase under RCP2.6 scenario (Figure 2.23 and Table 2.16). The RCP4.5 scenario portrays a small decline in annual precipitation, with projected reductions of around -8% by the end of the 21st century. For the RCP2.6 scenario, the precipitation changes are small, fluctuating around +2%. For the RCP8.5 scenario, the projections point to an annual precipitation decrease exceeding -20% by the end of the century.

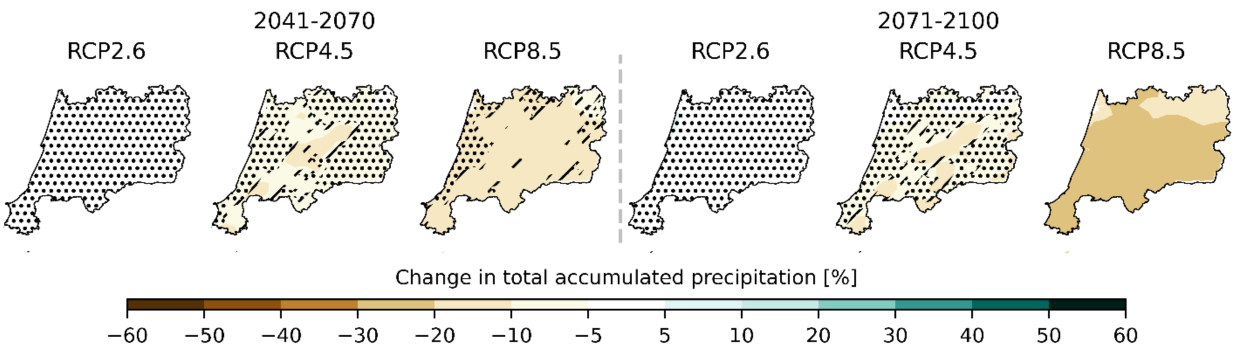


Figure 2.23 – Future projected relative changes in annual accumulated precipitation (%) for the Centro NUTS II region. Grid-points where the precipitation does not specify changes statistically significant are identified by dotted hatching.

Table 2.16 – Climatological annual mean accumulated precipitation (Pr) (mm) for the reference period (Historical – 1971-2000); and, future projected relative/absolute changes in annual accumulated precipitation (%/mm) for the Centro NUTS II region.

Centro	1971-2000	Differences	2041-2070			2071-2100		
	Historical		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
$Pr\ (mm)$	1090.6	ΔPr (%)	1.6	-8.3	-13.7	2.4	-8.0	-22.8
		$\Delta Pr\ (mm)$	14.0	-91.6	-146.5	25.2	-91.3	-243.6

As a result of the warming, the frequency and intensity of extreme temperatures events will undergo changes, which are less (more) pronounced under the RCP2.6 (RCP8.5) scenario (Figure 2.24). Concurrent with the rise in maximum temperatures, the occurrence of hot days[20], as well as summer[21] and extremely hot days[22], is projected to escalate. In the historical period (1971-2000), the number of hot days ranges between 20 and 80 days from west to east. For the RCP4.5, more 30 hot days are expected at the end of the century. For the RCP2.6, the increase is around 18 days, but for the RCP8.5 the number of hot days is projected to increase around 60 days when compared to the historical period. Furthermore, heatwaves[23] are projected to become more frequent, intense, and longer lasting. In the historical period 1 to 2 heatwaves occur per year with a mean duration around 6 days per event. Under the RCP4.5, it is expected an increase in the number of heatwaves between 3 and 5 throughout the 21st century. Even under the RCP2.6, the

[20] Hot days: number of days where maximum temperature exceeds 30ºC.
[21] Summer days: number of days where maximum temperature exceeds 25ºC.
[22] Very hot days: number of days where maximum temperature exceeds 35ºC.
[23] Heatwave is defined as a period of five or more consecutive days with maximum temperature above the 90th percentile.

occurrence of more 3 heatwaves per year is projected. However, considering the RCP8.5, the projections point to more 9 heatwaves per year. Aligned with the increase in the number of heatwaves, the mean duration of these events is also projected to increase. For the RCP4.5, the mean duration of heatwaves is projected to increase around 2 days. A similar result is expected for the RCP2.6, whilst under the RCP8.5, the expected increase is between 3 and 5 more days in heatwave, when compared with the historical period. Aligned with the rising of minimum temperature, tropical nights[24] are expected to become more prevalent, while the incidence of cold days[25] will diminish. For the RCP4.5 the number of tropical nights is projected to increase up to more 50 nights per year, and for the RCP8.5 the projected changes may reach up to more 80 nights per year.

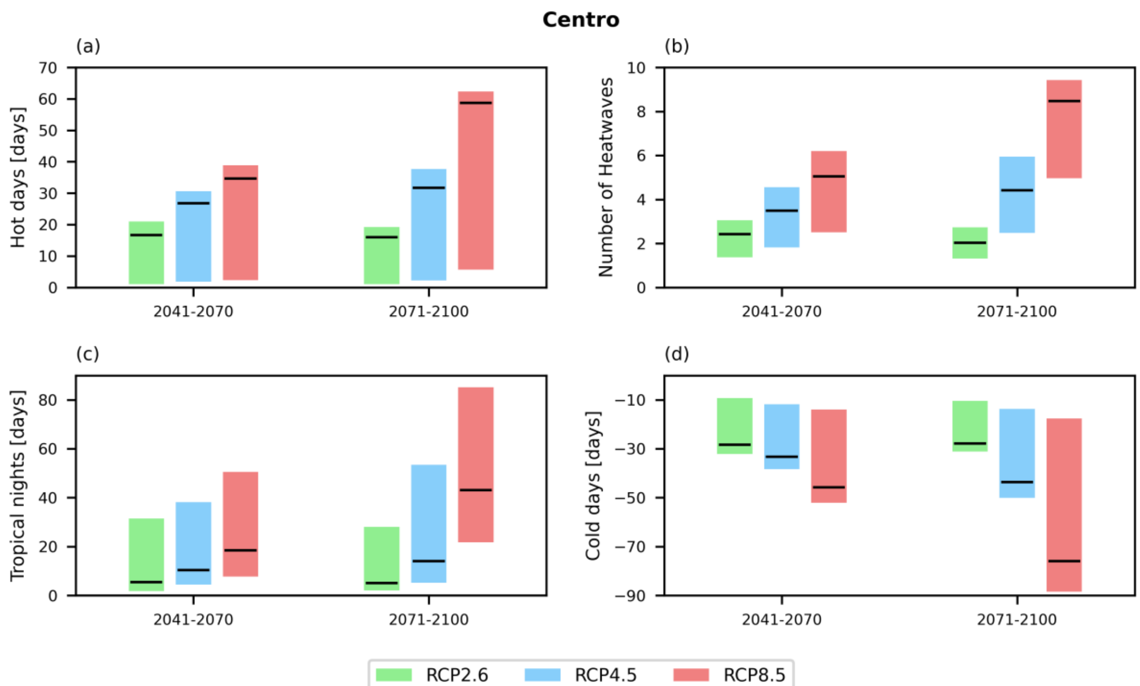


Figure 2.24 – Distribution of the projected changes in (a) hot days [days/year], (b) number of heatwaves per year, (c) tropical nights [days/year] and (d) cold days [days/year] for all gridpoints in Centro's region. The straight black line represents the mean value for the Centro's region. Individual boxes span from the spatial minimum to the maximum value of the Centro's region.

In line with the decline in mean accumulated precipitation, a reduction in the number of wet days[26] and, consequently, an increase in the number of dry days, is projected across the 21st century (Figure 2.25). For the RCP4.5 scenario, less 10 wet days are projected throughout the 21st century. For the RCP2.6 scenario, however, the changes are negligible throughout the century, with a slight decrease during the mid- and end-of the century of around 5 wet days. For the RCP8.5 scenario, the projections point to less 28 wet days at

[24] Tropical nights: number of days where minimum temperature exceeds 20ºC.
[25] Cold days: number of days where minimum temperature is below 7ºC.
[26] Wet days: number of days with precipitation exceeding 1 mm/day.

the end of the 21st century. Regarding the number of days with moderate[27] and heavy[28] precipitation, clear projected reductions are evident, especially under the RCP4.5 and RCP8.5 scenarios. Consequently, the number of consecutive dry days[29] is expected to increase, enhancing drying conditions. The maximum 5-day accumulated precipitation[30] is projected to increase especially in the northern part of the Centro's region. Under the RCP4.5 scenario, the increases can reach more 60 mm over the northern area (in the historical period the MaxPr5d value is around 400 mm). The results for the RCP2.6 scenario are similar to the ones for the RCP4.5. For the RCP8.5 scenario, the increase of maximum 5-day accumulated precipitation can reach more 90 mm but is rather heterogeneous. In spite of the projected decrease of the number of wet days, projections suggest a concentration of rainfall into shorter time frames, implying an intensification of moderate/heavy precipitation regardless of the scenario.

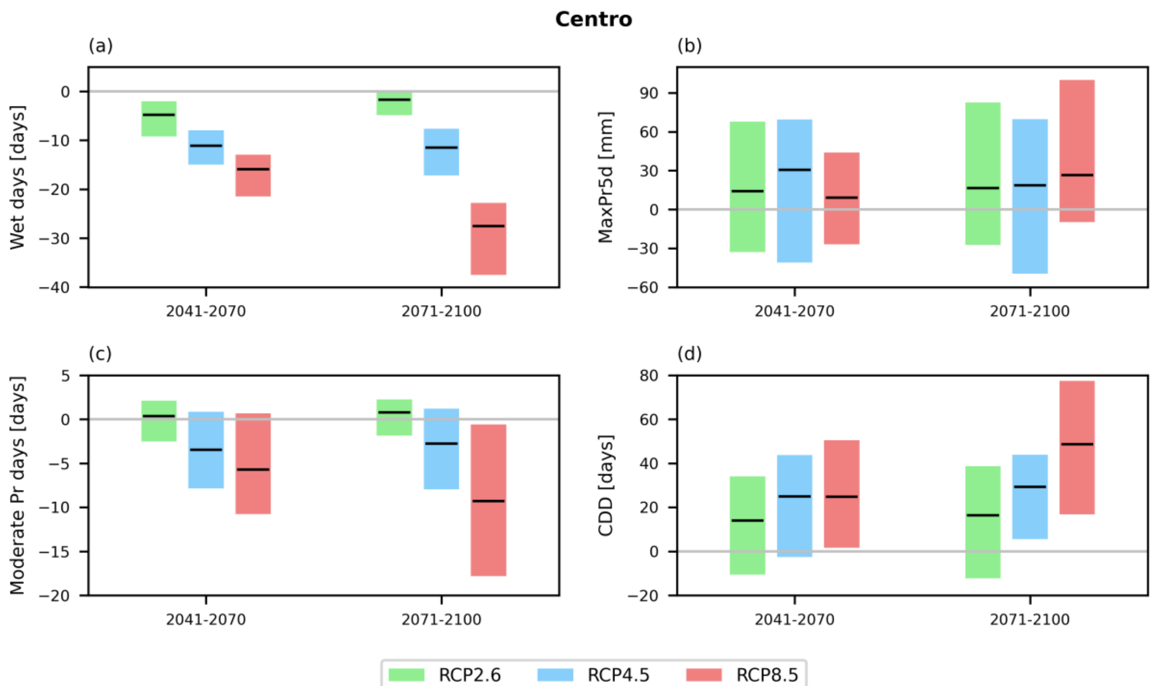


Figure 2.25 – Distribution of the projected changes in (a) wet days [days/year], (b) maximum of 5-day accumulated precipitation (MaxPr5d) [mm], (c) moderate precipitation days [days/year] and (d) consecutive dry days (CDD) [days] for all gridpoints in Centro's region. The straight black line represents the mean value for the Centro's region. Individual boxes span from the spatial minimum to the maximum value of the Centro's region.

A summary of confidence in the direction of projected changes in climate means and indices is presented in Table 2.17. The results give us confidence in climate projections presented here.

[27] Moderate precipitation days: number of days with precipitation exceeding 10 mm/day.
[28] Heavy precipitation days: number of days with precipitation exceeding 20 mm/day.
[29] Dry days: number of maximum consecutive dry days where precipitation is below 1 mm/day.
[30] Maximum of 5-day accumulated precipitation.

Table 2.17 – Summary of confidence in the direction of projected change in climate means and indices for the Centro NUTS II region. Temperature: climatological annual mean daily minimum (Tn) and maximum (Tx) temperature, hot days (Txg30), number of heatwaves per year (HWN), tropical nights (Tng20) and cold days (Tnl7); Precipitation: climatological annual mean accumulated precipitation (Pr), wet days (Prg1), maximum of 5-day accumulated precipitation (MaxPr5d), moderate precipitation days (Prg10) and consecutive dry days (CDD). A standard deviation of 0.25, 1, 2, 3 corresponds to a moderate, strong, very strong, severe increase/decrease of the variables. Values shown are ensemble median changes. Colours illustrate the model's agreement within the multi-model ensemble.

Centro							
		2041-2070			2071-2100		
		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Temperature	Tx	↑↑	↑↑↑	↑↑↑	↑↑	↑↑↑	↑↑↑
	Txg30	↑	↑↑	↑↑↑	↑	↑↑	↑↑↑
	HWN	↑	↑↑	↑↑↑	↑	↑↑↑	↑↑↑
	Tn	↑↑	↑↑↑	↑↑↑	↑↑	↑↑↑	↑↑↑
	Tnl7	↓↓	↓↓	↓↓↓	↓↓	↓↓↓	↓↓↓
	Tng20	↑	↑↑↑	↑↑↑	↑	↑↑↑	↑↑↑
Precipitation	Pr	⤨	↘	↘	⤨	↘	↘
	MaxPr5d	↗	↗	⤨	↗	↗	↗
	Prg1	↘	↘	↓	⤨	↘	↓
	Prg10	⤨	↘	↘	⤨	↘	↘
	CDD	↗	↑	↑	↑	↑	↑↑↑

↑↑↑	Change above 3 standard deviations
↑↑	Change above 2 standard deviations
↑	Change above 1 standard deviation
↗	Change above 0.25 standard deviations
⤨	Change between -0.25 and 0.25 standard deviations
↘	Change below -0.25 standard deviations
↓	Change below -1 standard deviation
↓↓	Change below -2 standard deviations
↓↓↓	Change below -3 standard deviations

(dark green)	High agreement: at least 80% of models show a positive change
(light green)	Low agreement: at least 50% of models show a positive change
(grey)	No agreement: models disagree on the direction of change
(light blue)	Low agreement: at least 50% of models show a negative change
(dark blue)	High agreement: at least 80% of models show a negative change

2.2.2. Water scarcity and stress on crops

NUTS II Centro includes, within its administrative boundaries, three River Basins, among which RH4 – Vouga, Mondego e Lis and RH5 – Tejo e Ribeiras do Oeste stand out (Figure 2.26). It contains several hydro-agricultural developments, with three notable ones due to their size: in RH5, the hydro-agricultural development of Cova da Beira, which draws water from three reservoirs within RH5, namely Capinha, Meimoa, Escarigo, and from Sabugal, located in RH3; the hydro-agricultural development of Baixo Mondego with water originating from the reservoirs of Aguieira, Raiva, Fronhas, and the Coimbra bridge dam, situated in RH4; and the hydro-agricultural development of Campina da Idanha-a-Nova, utilizing water from the Idanha reservoir, located in RH5.

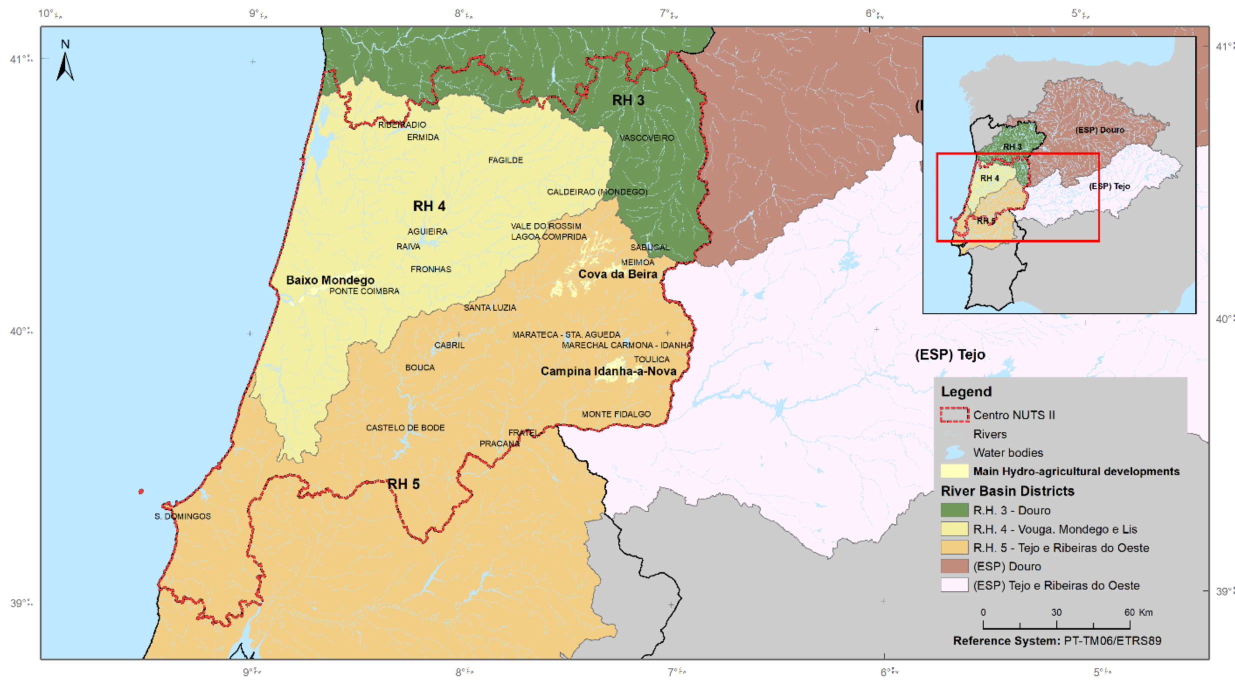


Figure 2.26 – NUTSII Centro and River Basins location: RH3 – Douro, RH4 Vouga, Mondego e Lis and RH5 – Tejo e Ribeiras do Oeste.

In 2022, the Centro region was the leading national producer of fresh fruits, namely pear, apple, and cherry, contributing 44.5% to the country's total production in these crops. However, the most significant crop for regional agriculture productivity is forage crops, accounting for 40.9% of the total tonnage. In this region, maize and oats for forage are prominent, followed by fresh fruit production with 17.4% of the region's total productivity, of which 7.9% from apples, 6.9% from pears, and the remainder is associated with other fruits.

Considering the full area of the main River Basins that cross NUTS II Centro, climate change scenario projections indicate a decrease in water yield for the RCP4.5 scenario (Figure 2.27). The trend of decreasing water yield becomes more pronounced for the scenario with higher concentrations of greenhouse gases in the atmosphere (RCP8.5). However, if concentration levels follow those outlined in the Paris Agreement throughout the 21st century (RCP2.6), the projections from the mid-century onwards show no particular significance for the water yield, projecting even a slight improvement. Nevertheless, it is essential to emphasize that this does not necessarily imply a reduction in water stress levels within the region. The dynamics of water stress depend on balancing water availability with demands. The Water Exploitation Index plus (WEI+) is a ratio comparing water use to renewable water resources and serves as a common tool in the European Union and Portugal for assessing this equilibrium.

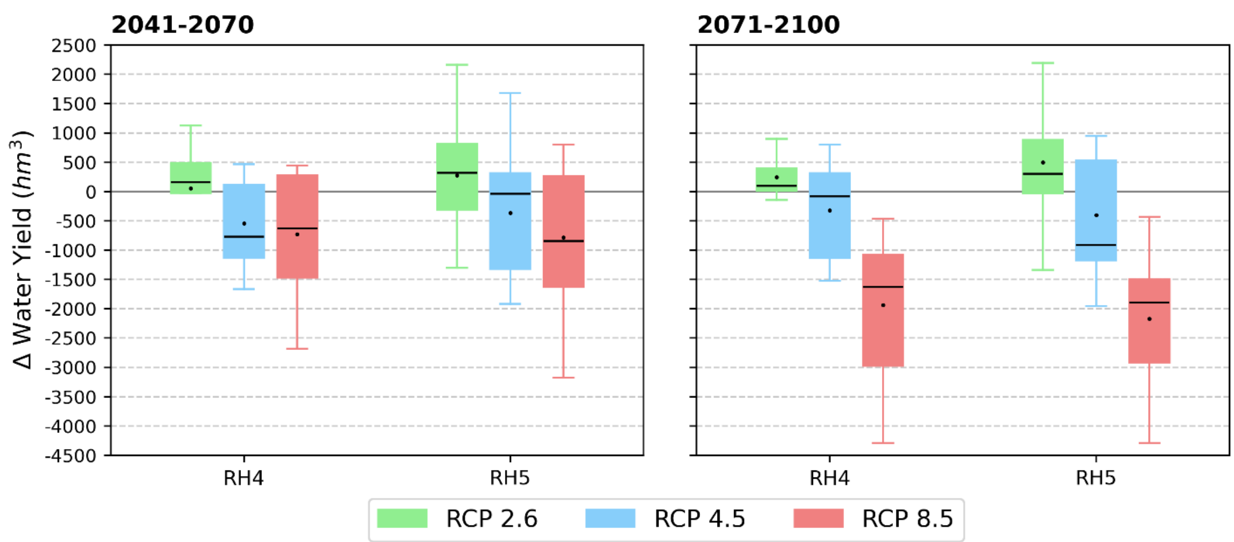


Figure 2.27 – Projected changes in averaged water yield (hm^3) for River Basins RH4 Vouga, Mondego e Lis and RH5 Tejo e Ribeiras do Oeste. Two future periods are shown: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5 and RCP8.5. The black line represents the ensemble median.

The Water Exploitation Index plus for the two principal River Basins Districts within NUTS II Centro is presented in Figure 2.28. Generally, under the RCP4.5 scenario, minimal changes are observed. These changes range from a maximum increase of around +2 percentage points to values very close to +1. In contrast, the RCP8.5 scenario displays a clearer trend, showing an increase in WEI+, with the highest value approaching an additional 12 percentage points in RH5 for the period 2071-2100. Regarding the RCP2.6 scenario, the projected changes show no significant difference when compared with the historical situation.

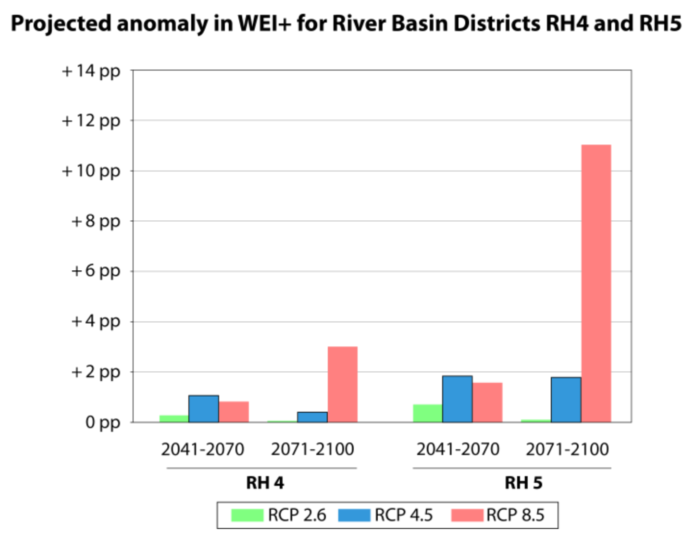


Figure 2.28 – Projected change in WEI+ (in percentage points) for River Basins RH4 Vouga, Mondego e Lis and RH5 Tejo e Ribeiras do Oeste. Two future periods are shown: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5 and RCP8.5. The presented values refer to the ensemble median.

Climate change can affect both irrigation requirements and productivity of the main crops grown in mainland Portugal. Table 2.18 illustrates these impacts on four crops: maize silage, grape, corn, and olive grove, representing 25.9%, 14,9%, 14.1%, 2.3%, and of the crop's productivity considered in NUTS II Centro. For olive groves, relative stability is observed across various climate change scenarios. However, a trend of decreasing productivity is noted for vineyards, maize silage, and grain corn, which could lead to a production decrease of up to -10.6% for grain corn in RCP4.5, compared to current productivity levels.

Considering all costs and benefits due to climate change in crops, the overall economic losses can amount to more than 153 million euros per year for the time frame 2041-2070 and more than 183 million euros for the period 2071-2100 in RCP4.5. Economic losses in productivity are related to modifications in climatic conditions for the crops currently developed in the region due to changes in plant phenology.

Table 2.18 – Projected changes in productivity in average % for corn silage, grape, grain corn and olive grove in NUT II Centro for two future periods: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5 and RCP8.5. The presented values refer to the ensemble median.

NUTS II Centro	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Corn Silage	-2.5%	-4.8%	-7.3%	-3.2%	-3.9%	-12.1%
Grape	-1.5%	-3.1%	-2.4%	-0.2%	-2.2%	-4.3%
Corn	-5%	-8%	-13.8%	-4%	-10.6%	-18.9%
Olive grove	-0.3%	-0.6%	-0.9%	-0.3%	-0.6%	-1.2%

Apart from the need for a careful assessment for the construction of new reservoirs, with updated meteorological and hydrological information, considering compliance with the DNSH (Do No Significant Harm) principle and also, proof that it continues to be an option in climate change scenarios (climate-proof), ensuring resilience now and in the future, it is imperative, firstly, to make a strong commitment to efficiency measures. Action should therefore consider minimizing losses to insignificant levels, reducing natural water consumption, which can be replaced in part by alternative sources such as water for reuse, changing crops to crops more adapted to existing conditions, among others. Therefore, the exercise presented focuses on identifying measures that allow the effects of the increase in the scarcity index, which currently exists, to be nullified throughout the 21st century and for different climate scenarios, through solutions that essentially affect the demand side.

To adapt the NUTS II Centro region to the projected impacts of climate change on water and agroforestry sectors, it is proposed that initial measures to be implemented should be of the no-regrets type, notably promoting the reduction of losses in the distribution network in hydro-agricultural developments and increasing irrigation efficiency throughout the region. Currently, the reality in the hydro-agricultural developments of the region varies significantly. For example, hydro-agricultural developments like Óbidos report 10.8% of losses in the distribution network, while others, namely Alvega or Idanha-a-Nova report losses of 40%. This measure proposes that all irrigation perimeters achieve distribution network efficiency levels exceeding 90%.

In terms of irrigation efficiency, significant progress has been made in recent years namely in fresh fruit production, but there is still room for improvement. Therefore, it is assessed that all irrigation in applicable crops transition to using drip irrigation systems, where irrigation efficiency typically ranges between 90-95%. In the Centro region, the adoption of this irrigation method for forage crops would be particularly relevant. Additionally, it is advisable to consider reducing water losses in the distribution network for urban purposes, as the overall average of losses is currently reported around 26.2%, considering the entire NUTS II region, with several water managing entities reporting losses around or up to 40%.

Subsequently, the simulations include a win-win measure that consists of the implementation of techniques promoting greater water retention in the soil (e.g., direct seeding, mulching) and the creation of water retention landscapes (e.g., creating ponds, planting in valleys and berms). This can contribute to a longer maintenance of the balance between water supply and demand in NUTS II through transformative adaptation.

The usage of water for reuse (a no-regrets measure) is also a viable solution, although its implementation is primarily directed towards urban or agricultural areas near urban clusters.

It is also crucial to ensure the success of the suggested adaptation actions by raising awareness and providing training to farmers. Farmer training should cover adaptive agricultural practices to help them cope with changing conditions, including the implementation of water management techniques, the introduction of drought-resistant crops, and the adjustment of planting and harvesting schedules. In this context, it is worth noting that the impacts of climate change will affect not only water availability but also agricultural productivity. Even if all plant water and nutrient needs are met, productivity losses will occur in scenarios with higher greenhouse gas emissions/concentrations over the century due to changes in plant phenology.

Adaptation in RH4 Vouga, Mondego e Lis[31]

In economic terms, the projected impacts of climate change on water availability for RH4 could result in losses averaging up to 722 thousand euros per year in RCP4.5 for the time frame 2041-2070 and more than 74 thousand euros for the period 2071-2100. Considering other scenarios, gains can vary on average up to 148 thousand euros (RCP2.6 period 2071-2100), while losses can almost reach 1.5 million euros on average per year (RCP8.5 period 2071-2100).

In this River Basin, a decrease in the average annual volume stored in the reservoirs is projected, with values that can reach -4.1% in the RCP4.5 scenario for the time frame 2041-2070 (Table 2.19). This situation is more pronounced in the RCP8.5 scenario, where the decrease could reach -8.5% by the end of the century. In contrast, for the RCP2.6 scenario, a small increase in average stored volumes is projected.

Table 2.19 – Projected changes in average annual volume stored in reservoirs in % for RH4, considering two future periods (anomaly) 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. The presented values refer to the ensemble median.

River Basins (RH4)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Reservoirs Availability	+0.1%	-4.1%	-3.3%	+1.4%	-1.2%	-8.5%

With the implementation of the above-mentioned adaptation measures for RH4, the identified economic impacts could be minimized in this River Basin, and some benefits would be achieved. Table 2.20 shows the overall results for RH4 with the percentual changes to the Water Exploitation Index Plus with the implementation of each of the following adaptation measures: reducing system water loss and leakages, improving irrigation efficiency, selection of crops better suited to climate change projections, and wastewater recycling and reuse.

Table 2.20 – Projected change in WEI+ (in percentage points) for RH4 are shown considering two future periods: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. The presented anomalies refer to the ensemble median and consider the following factors: no adaptation, the reduction of system water loss and leakages, the improvement of irrigation efficiency, the selection of crops better suited to climate change projections, and wastewater recycling and reuse.

River Basins (RH4)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Climate change impacts (no adaptation)	+0.26 pp	+1.06 pp	+0.82 pp	+0.04 pp	+0.40 pp	+2.99 pp
Reducing system water loss and leakages	+0.23 pp	+1.00 pp	+0.78 pp	-0.02 pp	+0.38 pp	+2.90 pp

[31] For the adaptation in RH3, please refer to the Adaptation storyline for NUTS II Norte.

River Basins (RH4)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Improving irrigation efficiency (entails reducing system water loss and leakages simultaneously)	+0.05 pp	+0.67 pp	+0.54 pp	-0.37 pp	+0.27 pp	+2.46 pp
Changing current irrigated crops (entails reducing system water loss and leakages simultaneously)	-0.77 pp	-0.36 pp	-0.36 pp	-1.11 pp	-0.37 pp	+0.97 pp
Wastewater for reuse (entails reducing system water loss and leakages simultaneously)	-1.14 pp	-0.64 pp	-0.52 pp	-1.25 pp	-0.82 pp	+0.75 pp

All of the individually modelled measures bring some benefit to the region by reducing the anomalies projected for WEI+. The measure that brings the most benefits, among those that were modelled, involves wastewater recycling and reuse in combination with reducing system water loss and leakages on hydro-agricultural developments. It is noteworthy that this measure can neutralize the impacts of climate changes on water balance or even improve the current situation, except for RCP8.5 by the end of the century.

Since not all discusses measures were modelled, the prioritization of all adaptation measures for RH4 is presented in Figure 2.29. The figure outlines the timeline for the full implementation of each measure aimed at mitigating the projected impacts of climate change. The proposed timeframe may be subject to change based on ongoing monitoring of the impacts of climate change, aiming to implement adaptive management over time.

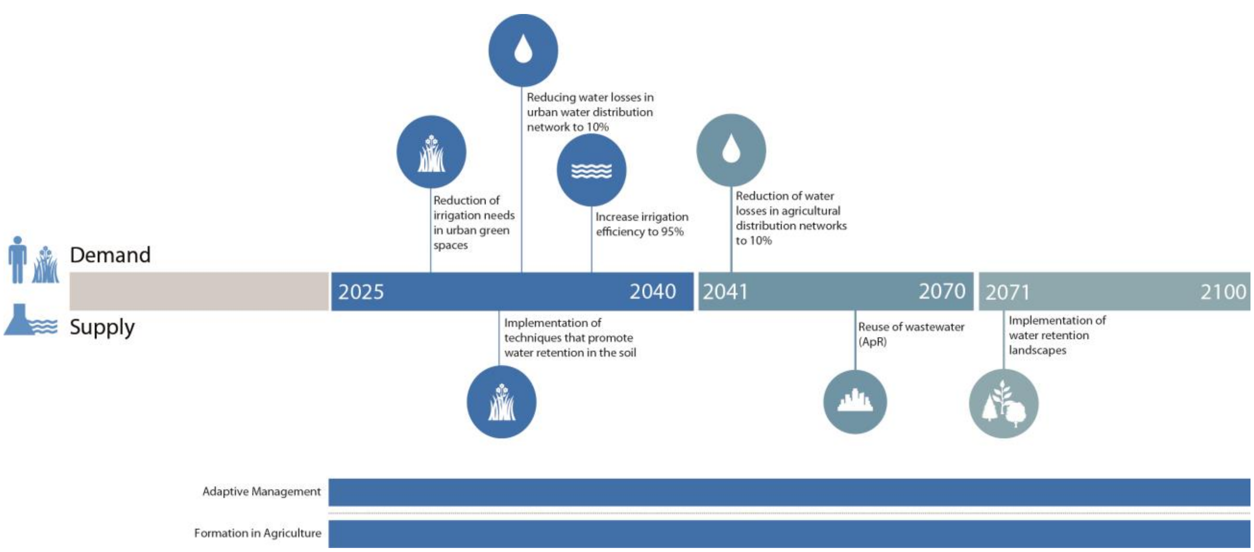


Figure 2.29 – Adaptation narrative for the water resources and agroforestry sectors in RH4 until 2100.

Adaptation in RH5 Tejo e Ribeiras do Oeste[32]

In economic terms, the projected impacts of climate change on water availability for RH5 could result in losses averaging up to 32 thousand euros per year in RCP4.5 for the time frame 2041-2070 and more than 793 thousand euros for the period 2071-2100. Considering other scenarios, gains can vary on average up to 276 thousand euros (RCP2.6 period 2041-2070), while losses can be as high as 1.6 million euros on average per year (RCP8.5 period 2071-2100).

In this River Basin, a decrease in the average annual volume stored in the reservoirs is projected, with values that can reach more than -3% in the RCP4.5 scenario (Table 2.21). This situation is more pronounced in the RCP8.5 scenario, where the decrease could reach -9% by the end of the century. For the RCP2.6 scenario, it is projected that there will be a slight decrease in average stored volumes in reservoirs, but it is not considered significant.

Table 2.21 – Projected changes in average annual volume stored in reservoirs in % for RH5, considering two future periods (anomaly) 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. The presented values refer to the ensemble median.

River Basins (RH5)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Reservoirs Availability	-1.6%	-3.5%	-2.7%	-1.4%	-2.9%	-9.0%

With the implementation of the above-mentioned adaptation measures for RH5, the identified economic impacts could be minimized in these river basins, and some benefits would be achieved. Table 2.22 shows the overall results for RH5 with the percentual changes to the Water Exploitation Index Plus (WEI+) with the implementation of each of the following adaptation measures: reducing system water loss and leakages, improving irrigation efficiency, selection of crops better suited to climate change projections, and wastewater recycling and reuse.

Table 2.22 – Projected change in WEI+ (in percentage points) for RH5 are shown considering two future periods: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. The presented values refer to the ensemble median and consider the following factors: no adaptation, the reduction of system water loss and leakages, the improvement of irrigation efficiency, the selection of crops better suited to climate change projections, and wastewater recycling and reuse.

River Basins (RH5)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Climate change impacts (no adaptation)	+0.69 pp	+1.82 pp	+1.60 pp	+0.10 pp	+1.80 pp	+11.04 pp

[32] For the adaptation in RH3, please refer to the Adaptation storyline for NUTS II Norte.

River Basins (RH5)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Reducing system water loss and leakages	+0.46 pp	+1.45 pp	+1.36 pp	-0.24 pp	+1.52 pp	+10.00 pp
Improving irrigation efficiency (entails reducing system water loss and leakages simultaneously)	-0.39 pp	+0.98 pp	+0.90 pp	-0.95 pp	+0.94 pp	+8.22 pp
Changing current irrigated crops (entails reducing system water loss and leakages simultaneously)	-1.57 pp	+0.12 pp	+0.08 pp	-2.02 pp	-0.52 pp	+4.97 pp
Wastewater for reuse (entails reducing system water loss and leakages simultaneously)	-3.95 pp	-2.40 pp	-2.38 pp	-4.23 pp	-2.61 pp	+0.31 pp

All the individually modelled measures contribute to benefiting the region by reducing the disparities between the projected and the scenario of no adaptation. The measure that brings the most benefits to the region, among those that were modelled, involves wastewater recycling and reuse in combination with reducing system water loss and leakages on hydro-agricultural developments. In this case the anomaly in WEI+ can be reduced by up to 10 percentage points at the end of the century. It is noteworthy that this measure can neutralize the impacts of climate changes on water balance or even improve the current situation, with the exception of RCP8.5 at the end of the century.

Since not all discusses measures were modelled, the prioritization of all adaptation measures for RH5 is presented in Figure 2.30. The figure outlines the timeline for the full implementation of each measure aimed at mitigating the projected impacts of climate change. The proposed timeframe may be subject to change based on ongoing monitoring of the impacts of climate change, aiming to implement adaptive management over time.

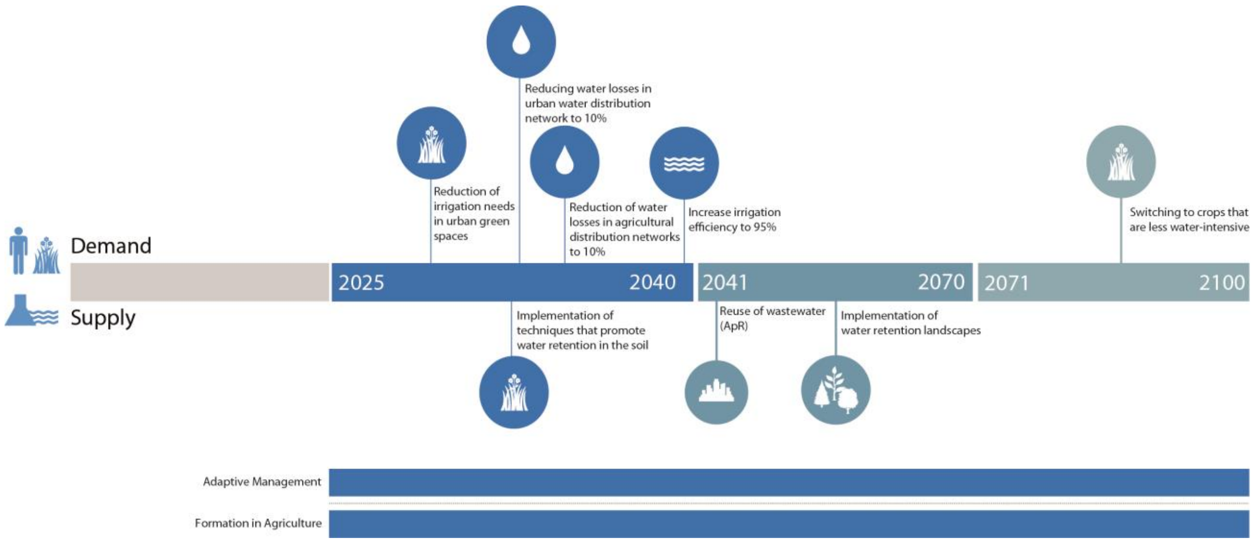


Figure 2.30 – Adaptation narrative for the water resources and agroforestry sectors in RH5 until 2100.

2.2.3. Coastal flooding

The Centro region coastline comprehends a diversified coastal environment extending for about 250 km (Figure 2.31). This stretch, although mainly composed of long sandy beaches (*e.g.*, Torrão do Lameiro, Torreira, São Jacinto, Areão, Mira, Osso da Baleia), is intersected by the largest Portuguese lagoon system, the Ria de Aveiro, the Mondego River estuary (at Figueira da Foz), the São Martinho do Porto bay, the Óbidos coastal lagoon, and the Peniche and Baleal peninsulas. Sandy beaches with adherent structures are often present (*e.g.*, Esmoriz, Vagueira, Cova Gala) as well as urban beaches (*e.g.*, Costa Nova, Figueira da Foz, Nazaré). The southernmost portion of the domain is characterized by an approximately 30 km stretch of rocky cliffs and pocketed beaches (*e.g.*, Gralha, Porto das Barcas, Porto Dinheiro, Valmitão).

This coastal region is shown to be particularly vulnerable to the impacts of rising sea levels and changes in wave climate patterns (the reader is referred to the WP4.5/6 dynamic modelling report), exhibiting the largest historical and future projected erosion trends at a national scale. Some of the most vulnerable coastal areas of the Centro region can be found at Esmoriz, Furadouro, Costa Nova, Vagueira and Cova Gala.

Figure 2.31 – The Centro NUTSII region, depicting the most relevant locations in terms of projected coastal vulnerability.

Overall, the vulnerability assessment carried for the Centro region revealed highly vulnerable areas throughout most of the coastline, as soon as by the mid-21st century, and under a moderate concentrations scenario (RCP4.5; Figure 2.32). The amount of threatened areas was shown to increase towards the end of the 21st century, and for the higher-concentration scenario (RCP8.5). Although high erosion trends were found for the sandy ocean-facing coastlines, the ones facing inland waters were shown to generally become more vulnerable to the projected increases in the total water levels[33], mostly due to the topographic configuration of the terrain near the coastal lagoons and estuaries, with extensive low-lying intertidal areas. Within the Centro region, moderate-to-high vulnerability can be expected near or across relevant population centers, such as Esmoriz, Cortegaça, Furadouro, the lowest portions of Aveiro city, and São Jacinto; Costa Nova, Vagueira and Mira (vulnerable to changes in both oceanic and inland waters' levels); Figueira da Foz harbor, Cova Gala, Vieira de Leiria, Nazaré, São Martinho do Porto, Óbidos lagoon and Sizandro River mouth. Bear in mind that highly vulnerable areas are projected to be threatened by extreme coastal flooding conditions associated to return periods as frequent as every 4 years. These results are consistently found

[33] The total water level (TWL) is given by the sum of the sea level rise (SLR), tide and storm surge components. For the ocean-facing coastlines, the run-up associated with a 99th percentile energy wave event is also considered.

after 2041, for both scenarios, despite small variations in the extension of the low, moderate and high vulnerability categories.

Considering the Centro region as a whole, and for the three classes of vulnerability adopted (low, medium and high, associated to the 100-, 25- and 4-year total water level return values) projections revealed 16.3-20.3 km^2 of vulnerable ocean-facing coastlines (beaches), and 75.3-85.0 km^2 of vulnerable coastlines facing inland waters (mostly in the Ria de Aveiro; Table 2.23), depending on the future period and scenario. Departing from the intermediate RCP4.5 scenario, on a trajectory closer to the RCP8.5, an increase up to 2.0 km^2 in the vulnerable areas of the Centro region is projected by 2100.

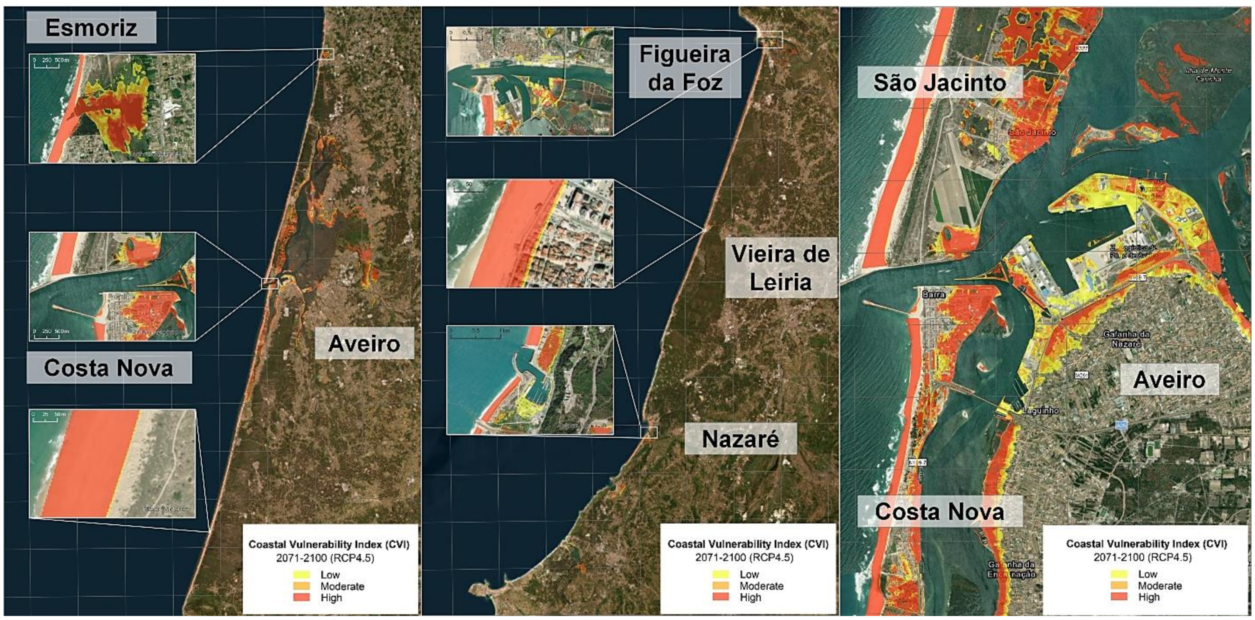


Figure 2.32 – Projected vulnerable areas along the Centro region by the end of the 21st century (2071-2100) under RCP4.5, with focus on the Ria de Aveiro coastal lagoon system, near Aveiro. The CVI is inversely related to the TWL 4-, 25- and 100-years return period values (*e.g.*, a high CVI is given to coastal areas projected to become flooded under a 4-year RP TWL).

Table 2.23 – Area (in km^2) of the vulnerable coastal stretches in the Centro region (grouped for the three classes of vulnerability), by the end of the 2041-2070 and 2071-2100 future periods, under both RCP4.5 and RCP8.5 scenarios.

Vulnerable coastal areas (km^2)				
Centro region	2041-2070		2071-2100	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Ocean-facing	16.3	18.5	19.6	20.3
Inland	59.0	59.6	63.4	64.7
Total	75.3	78.1	83.0	85.0

Considering the diverse coastal environments in the Centro region, different adaptation narratives have to be pursued, instead of a single common one. Figure 2.37 shows, similarly to Figure 2.17, the proposed adaptation pathways along the five identified environments for the Centro region. For each one, different pathways are shown, spanning from the present time until the end of the 21st century, and varying due to: (1) each coastal environment's expected response to changes in total water levels and wave characteristics (if facing the ocean), (2) the different possibilities in terms of adaptation strategies, and (3) any site-specific adaptation effort that was already carried in the recent past.

Sandy beaches with adherent structures
(e.g., Vagueira)

Low-lying sandy beaches
(e.g., Aveiro – São Jacinto)
Source: www.playocean.net

Pocket beaches and rocky cliffs
(e.g., Alcobaça – Praia da Gralha)

Urban beaches
(e.g., Figueira da Foz)

Inland waters
(e.g., Ria de Aveiro)

Figure 2.33 – Different coastal environments in the Centro NUTSII region. Specific adaptation pathways are built for each environment in Figure 2.37.

In general, and according to the current national-scale adaptation strategy (Pinto et al., 2020), artificial beach nourishment corresponds to a transversal protection measure against the fast erosion trends observed in this coastal stretch (Figure 2.35 and Figure 2.37). Artificial nourishment interventions are relatively standardized in the Centro region, especially at Costa Nova, with more than 13 million cubic meters deposited since 1965. This measure is projected to remain dominant during the next decade, at least, while the planning takes place for more complex accommodation and relocation measures (Figure 2.35 and Figure 2.37). Bear in mind, however, that artificial nourishments are usually quite localized, varying greatly in terms of frequency and intensity even within the same coastal environment, depending on sediment availability and overall cost-benefit ratios. At Costa Nova, for example, a strategy considering the obtention of 28 million cubic meters of sediment from an offshore borrow site is currently in place to allow the restocking of the most problematic areas (near the population center) by 600 thousand cubic meters every year. At Cova Gala, planned nourishments amount to 3.3 million cubic meters every 5 to 7 years, starting from 2025. Such interventions should halt, at least by half, the current verified erosion trends not only in the mentioned areas but also throughout several kilometers downdrift. Therefore, artificial nourishment is considered as the most viable adaptation measure for the urban and sandy beaches with adherent structures along the Centro region, at least until the beginning of the 2040s. Where applicable, the demolition of exposed illegal or non-essential structures should also be a priority within this timeframe (Figure 2.37).

The accommodation of currently existing adherent structures (*e.g.*, seawalls, tidal dykes and harbour structures; Figure 2.35) is shown as a functional option to protect the urbanized areas inland. Although it may be considered as a secondary measure in terms of priority, it is projected to become increasingly relevant towards the middle of the 21st century. Observe, for example, that the existing seawall at Cova Gala was not able to sustain the effects of the Hercules storm (in January 2014), with several overtopping reports. With the projected increase in total waters levels (mostly due to SLR), protection structures may require additional levels of protection. Note that due to long-term shoreline retreat, not only is artificial nourishment projected to become progressively ineffective (given the permanent flooding of the pre-existing beaches in the base of the adherent structures), but also are the low-lying areas surrounding the inland waters of Ria de Aveiro, Óbidos lagoon, among others, projected to become increasingly threatened. The required topographic height (relative to the National Vertical Datum CASCAIS1938) for the coastal protection structures to withstand the future projected extreme coastal events[34] is set at 7.06 m, under the intermediate RCP4.5 scenario (Figure 2.34). Excluding wave action, the required height for inland waters coastal protection structures is set at 3.29 m, in order to sustain a 100-year return period event by the end of the 21st century. Departing from the RCP4.5, on a trajectory closer to the RCP8.5, an increase of up to

[34] Considering a 99th percentile wave energy event over a 25-year TWL return value.

0.10 m (3.29 m → 3.39 m) is expected for the structures' heights facing inland waters, and an increase of up to 0.66 m (7.06 m → 7.72 m) is expected for the ocean-facing ones. These values should be considered as references to all ocean-facing and inland waters coastlines of the Centro region. Note, nevertheless, that coastal stretches with steeper slopes, usually present at highly anthropized ocean-facing segments (*e.g.*, Esmoriz, Cortegaça, Furadouro, Costa Nova, Vagueira, Mira, Cova Gala, Lavos, Leirosa, Pedrógão, Vieira de Leiria), may expect higher run-up values.

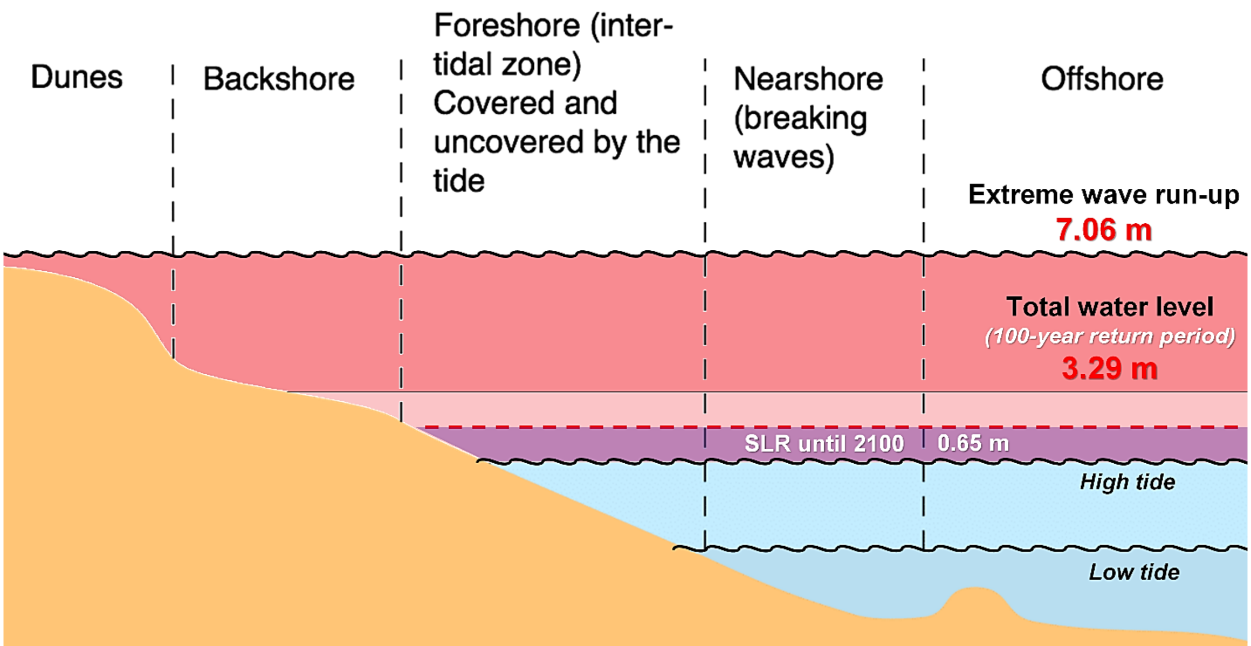


Figure 2.34 – Schematic depiction of how changes in total water levels and run-up may lead to coastal flooding. Note that while for inland waters the maximum coastal flooding topographic height is projected to be set at 3.29 m, for ocean-facing coastlines the value is projected to be set at 7.06 m (values for the RCP4.5 scenario by the end of the 21st century).

While accommodation may still be a viable option towards the end of the 21st century (especially for inland waters; Figure 2.35), planned relocation actions should become the most cost-effective way to deal with continuously rising sea levels and extreme coastal flooding along most of the Centro coastlines north of São Pedro de Moel, as soon as by the mid-21st century, both ocean-facing (*e.g.*, Esmoriz, Cortegaça, Furadouro, Vagueira, Mira, Cova Gala, Leirosa, Pedrógão, Vieira de Leiria; Figure 2.37; Table 2.24) and surrounding inland waters (*e.g.*, Ria de Aveiro). Further south, the different morphology of the coastline, with sandy and rocky cliffs is found to be enough to protect most local populations from changes in the sea levels (with exceptions, nevertheless, such as in São Martinho do Porto and the low-lying areas neat the Óbidos coastal lagoon). Artificial nourishment interventions should be considered as a local option, if the economic or natural value of the beach justifies it. It should be noted that most of the small or pocketed beaches in the southernmost portion of the domain are projected to disappear or be extensively reduced towards the end of the 21st century.

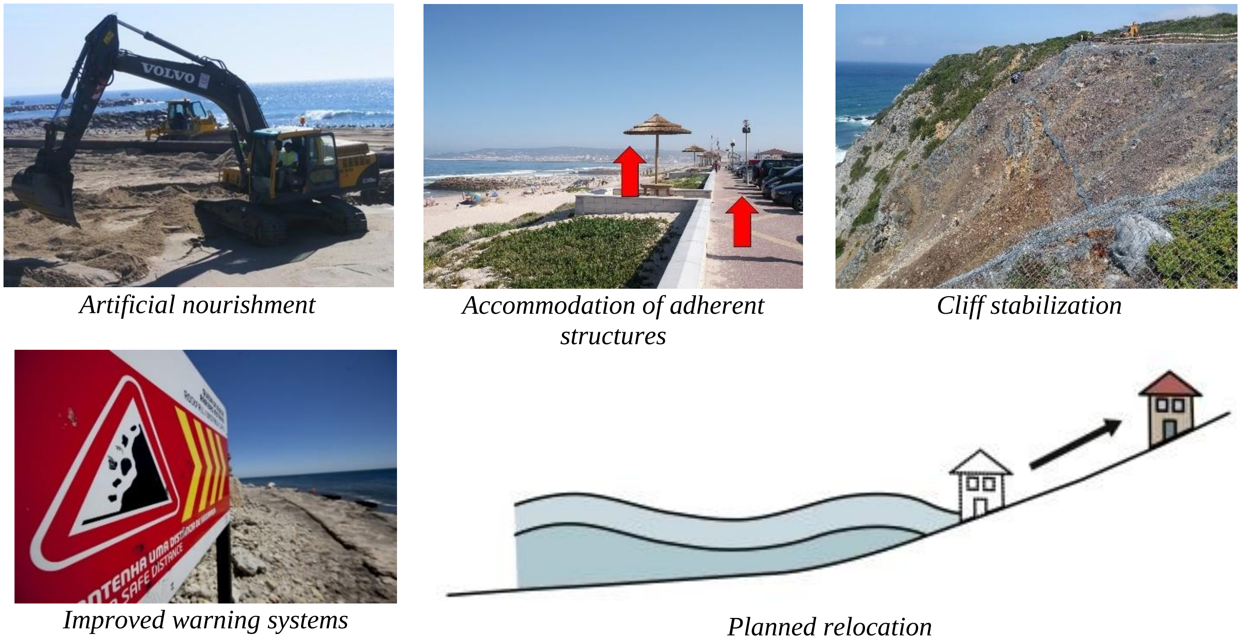


Figure 2.35 – Examples of adaptation measures to be applied in the Centro region, and present in the proposed adaptation pathways of Figure 2.37.

The demographic and cost-benefit analysis performed for the Centro region is expressed in Table 2.24. Under the RCP4.5 scenario, more than 12100 habitants (according to the CENSOS2021) are projected to become vulnerable[35] until the end of the 21st century, from over 6100 vulnerable buildings. Total inaction costs related to patrimonial losses (without adaptation measures; TIC) top at over 1784 and 2086 million € by 2070 and 2100, respectively, for all coastlines (both inland and ocean-facing ones). The portion of the TIC associated to each coastal municipality of the Centro region is depicted in Figure 2.36. Total adaptation costs (TAC), calculated exclusively for ocean-facing coastlines, are set at 1025 and 1628 million €, exceeding the TIC for the same coastlines (296 and 477 million €). Therefore, while fostering adaptation strategies is overall recommended for the Centro region, the advantages of reducing local populations' exposure to coastal hazards are significant, and relocation efforts are suggested for the most urbanized ocean-facing coastal stretches (Figure 2.37), due to the unbalanced cost-benefit ratio of the remaining adaptation measures in these coastal environments.

Table 2.24 – Demographic (number of vulnerable residents and buildings projected as vulnerable, *i.e.*, under CVI) and economic cost analysis considering the total inaction costs (TIC) and the total adaptation costs (TAC) in the Centro region, by 2070 (end of the 2041-2070 period) and 2100 (end of the 2070-2100 period), under the RCP4.5 scenario.

Centro region (RCP4.5 scenario)	2070	2100
Number of residents under CVI	10783	12169
Number of buildings under CVI	5338	6125

[35] *i.e.*, exposed to at least a 100-year return period flooding event.

TIC from 2024 onwards – maximum (M€)	1784.7	2087.0
TIC from 2024 onwards – maximum for ocean-facing coastlines (M€)	296.3	476.8
TAC from 2024 onwards for ocean-facing coastlines (M€)	1025.4	1627.9
Annualized maximum TIC (M€/year)	38.0	27.1
Annualized maximum TIC for ocean-facing coastlines (M€)	6.3	6.2
Annualized TAC for ocean-facing coastlines (M€/year)	21.8	21.1

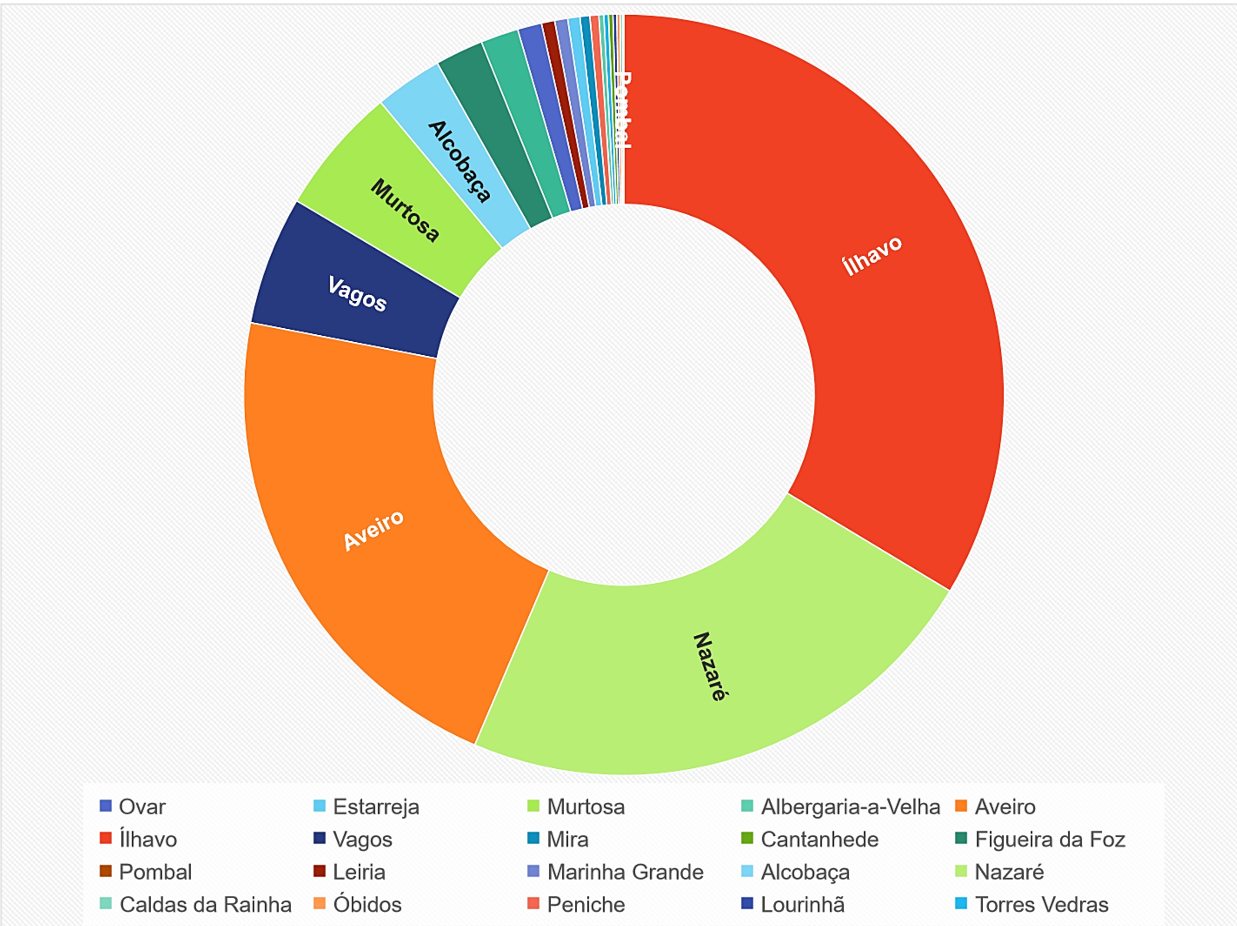


Figure 2.36 – Portion of the TIC (until 2100 under RCP4.5) associated to each coastal municipality of the Centro region.

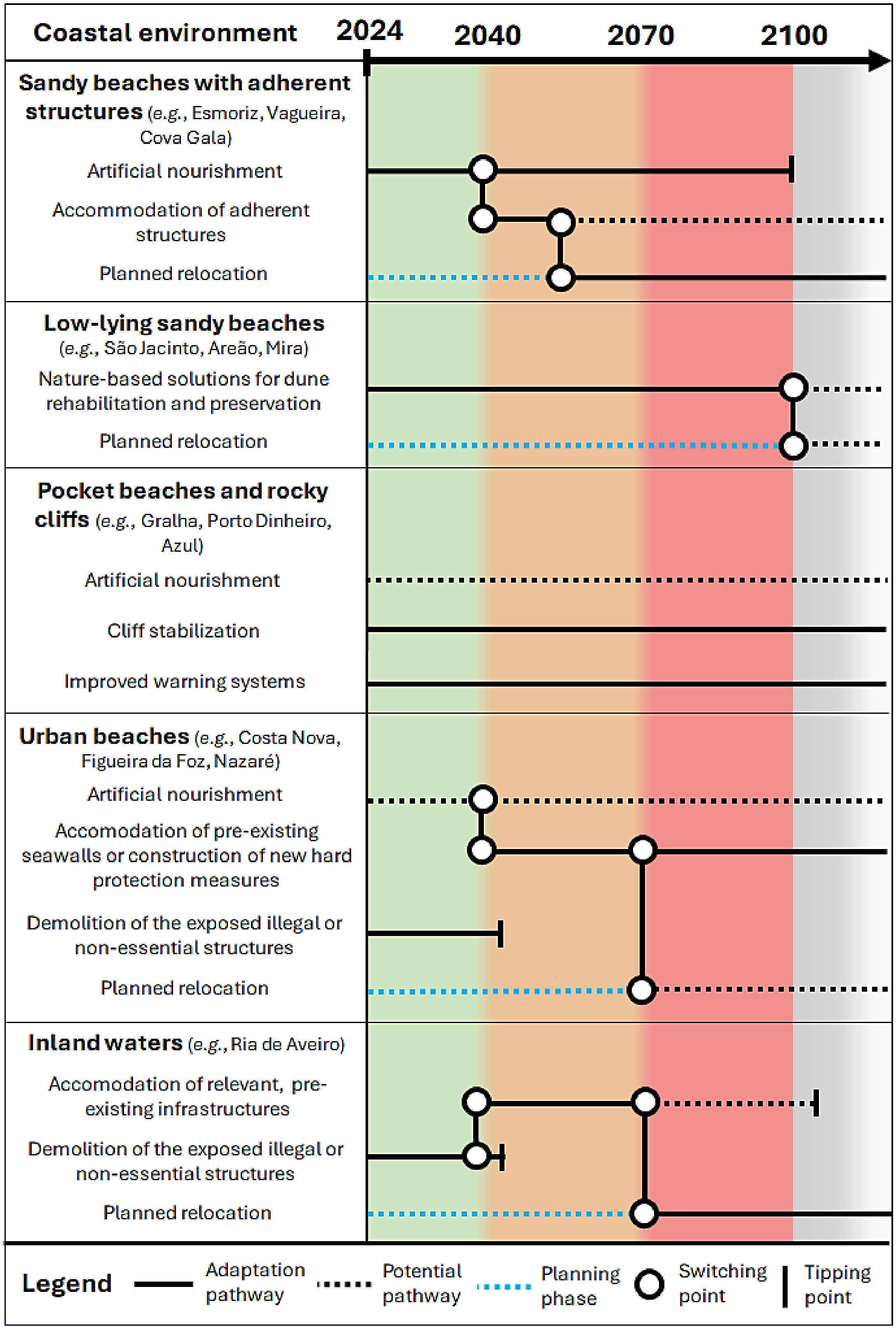


Figure 2.37 – Proposed adaptation pathways along the five identified environments present in the Centro NUTSII region, departing from the year 2024, and spanning until the end of the 21st century. The pathways in full correspond to the most viable adaptation strategy for each coastal environment.

2.2.4. Forest fires

Portugal's Centro region is historically characterised by large wildfires (Figure 2.38), where the 2017 Pedrógão or the 2022 Serra da Estrela wildfires are some of the most prominent examples. This region is typically affected by an array of hot and dry extreme events, such as heatwaves and droughts that increase the stress of the vegetation and ultimately, with an ignition, end up in large wildfires that are seen by satellite with very energetic values. To comprehend the variable distribution and damage caused by wildfires and to devise practical adaptation options, it is crucial to consider several factors. Among these, meteorological conditions emerge as pivotal in influencing fire danger. Weather and climate, along with vegetation condition, composition, and human factors, play indispensable roles in shaping fire regimes.

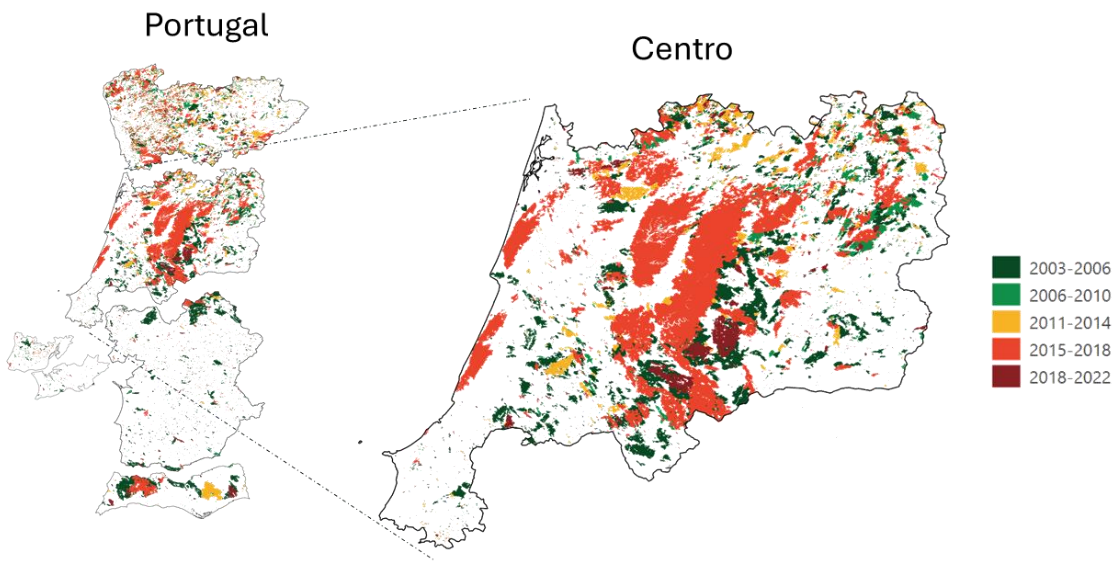


Figure 2.38 – Highlight of Centro burned area, with the colours representing the period where the last occurrence took place.

Meteorology not only defines the composition and structure of vegetation fuels but also holds a central position in determining the susceptibility of these fuels to fire. Human activities and vegetation management practices contribute to the present state of vegetation fuels, while their typology is intricately linked to the broader ecological domains they inhabit. Weather effects exert a profound influence on the vulnerability of vegetation fuels to ignition. They can control the moisture content of different fuels, enabling rapid wetting or drying of fine fuels such as litter, needles, mosses, and twigs. The response is comparatively slower for coarser wooden fuels. The moisture levels in these various fuels, coupled with meteorological factors like wind speed, collectively influence the ease of ignition, potential propagation, and severity of a fire.

Recognizing the pivotal importance of meteorology in fire danger assessment is imperative for developing effective strategies for wildfire preparedness and adaptation. A comprehensive understanding of how meteorological conditions interact with other factors contributes significantly to the ability to predict and manage wildfires. Hence, meteorologic danger was assessed by taking advantage of the enhanced Fire Weather Index (FWIe).

Hence, the future meteorological danger was assessed by taking advantage of the enhanced Fire Weather Index (FWIe)[36]. It is projected a significant increase in the number of extreme fire danger days (Table 2.25), i.e., the number of days where FWIe is extremely high. For the RCP4.5 more 14 (17) days in extreme fire danger for the mid- (end-) century are projected with respect to the historical values; slighter changes for the RCP2.6 are projected, from additional + 7 to +6 days, and for the RCP8.5 the number of extreme fire danger can escalate more +35 at the end of the century, more than tripling the 15-days mark observed in the historical climate.

Table 2.25 – Additional number of days per extended summer (June to September) with extreme fire danger for different emission scenarios compared to the present climate.

Centro	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Additional days (present climate = 15 days)	+7	+14	+19	+6	+17	+35

Parque Natural da Serra da Estrela was recently afflicted with a large wildfire in 2022 (Figure 2.39). Indeed, this region is also affected by a strong increase in the number of days with extreme fire danger when considering medium to long-term projections, where in the worst-case scenario almost a third of the summer presents extreme danger.

[36] The enhanced FWI is a meteorological fire danger index that combines an atmospheric instability parameter.

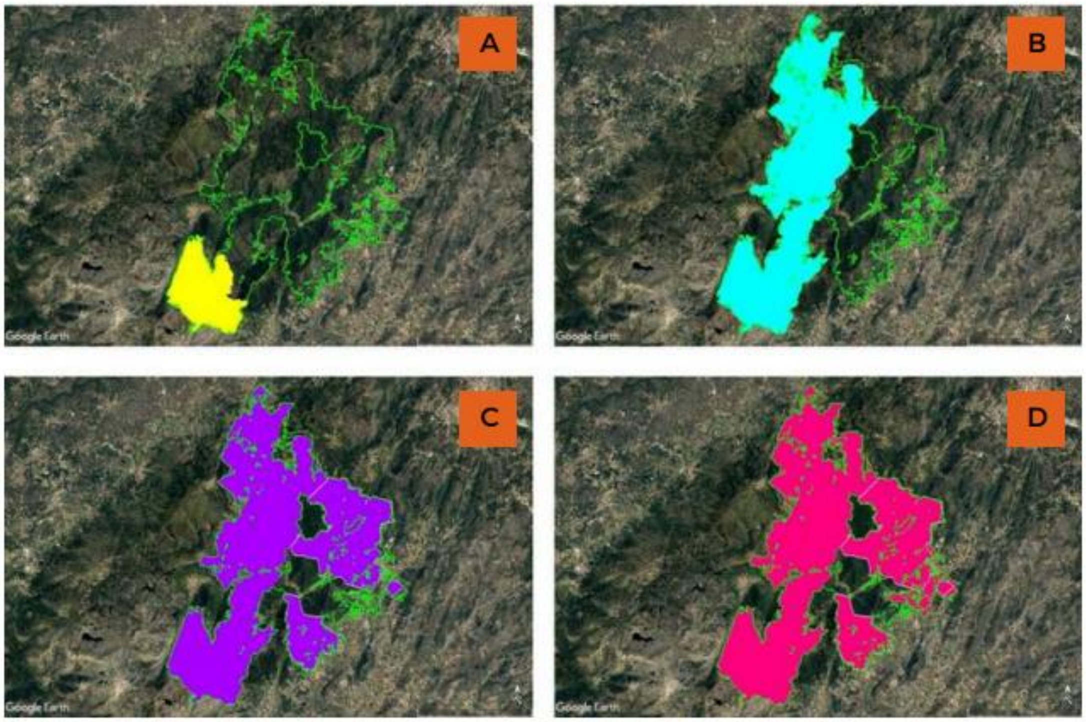


Figure 2.39 – Evolution of the 2022 Serra da Estrela wildfire in 4 different phases, with the total burnt area delimited in green, which totals around 27,000 ha (source: Relatório final Grupo de peritos dos incêndios rurais).

It is important to note that in medium and long-term periods the number of days are twofold when compared to the past, and that for the high-emissions scenario the number of days may triple. Return periods of burned areas reaching 75,000 ha, which occurred once every 3 years in the historical period are expected to occur much more frequently in the future, occurring once every year and a half for RCP4.5 (2 years for RCP2.6 and yearly for RCP8.5) if no adaptation measures are pursued (Figure 2.40).

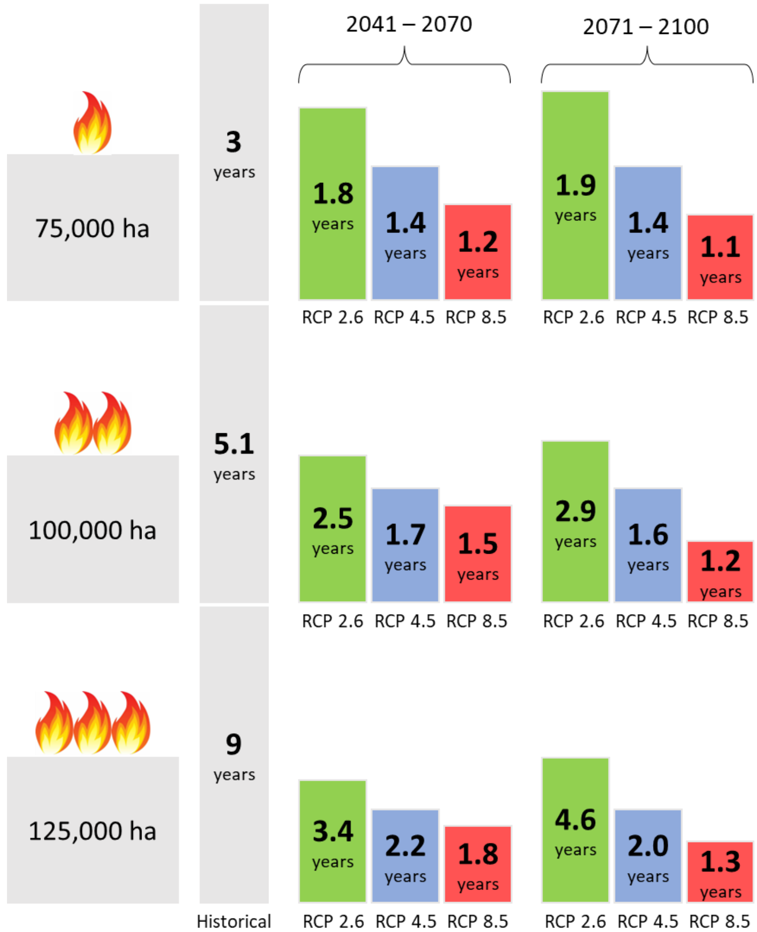


Figure 2.40 – Return periods of three large burned area thresholds, taking into account the no adaptation pathway for the Centro region.

In the Centro region of Portugal, the implementation of adaptation strategies is critical to mitigate the escalating threat of forest fires and their associated losses. Recognizing the urgency of the situation, a multifaceted approach is being devised, drawing upon insights from various fields of expertise and tailored to the unique challenges faced by the region. Efforts are underway to minimize the extent of burned areas and enhance post-fire land management practices. By reducing the annual burned area and strategically reforesting with resilient species, the region aims to not only mitigate fire risks but also bolster carbon sequestration and ecosystem resilience. Furthermore, educational initiatives targeting individuals of all ages are being implemented to foster a culture of fire prevention and safety, with the goal of reducing fire ignitions by up to 50%. Similarly, in the Centro region, which encompasses diverse landscapes and ecosystems, adaptation strategies focus on reducing the frequency and severity of wildfires through targeted interventions. By leveraging meteorological forecasts and early warning systems, authorities can prioritize resources and respond swiftly to extreme fire danger days, thereby reducing the number of very energetic fires and associated losses. This focused approach could lead to significant cost savings, with each avoided large wildfire translating into millions of euros saved. Overall, the cost of adaptation measures is offset by the substantial savings achieved through proactive wildfire prevention efforts. By investing in forest management practices, educational campaigns, and early warning systems, the Centro region aims to build resilience to the growing threat of forest fires, ensuring the long-term sustainability of its natural environments and communities.

When considering the 2022 Serra da Estrela wildfire, where 27,000 ha burned and losses were estimated at 35 million euros, it seems a crucial threat that extreme meteorological danger days are expected to be four times more, with almost half of the summer in such condition. The probability of having such a wildfire in the future may double in RCP4.5 depending on the energy that is released. In the current climate context, assuming similar losses per ha, the cumulative financial toll of forest fires in the Centro region over the past 20 years stands at around 1,714 million euros, i.e., about 85 million euros/year.

From the probabilistic model developed in the context of RNA2100, it is possible to estimate that the likelihood of having forest fires of similar intensity as the 2022 Serra da Estrela event can be near 2 times the historical frequency, in agreement with the probability of exceedance of a given fire radiative power under the RCP4.5. Without proactive adaptation measures, the projected losses (Table 2.26) could escalate to nearly 163 million euros/year under RCP4.5 (almost doubling the 85 million euros/year mark).

Table 2.26 – Projected losses without implementing adaptation measures, in million euro/year for Centro region.

Centro (No adaptation)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Losses (million euro/year)	159	163	175	126	163	223

In the Serra da Estrela and other natural parks located in the Centro region, the preservation of its unique and diverse forests is of paramount importance. Adaptation strategies play a crucial role in safeguarding these valuable ecosystems and mitigating the escalating threat of forest fires. Given the ecological significance of Serra da Estrela's forests, adaptation measures aim to minimize the extent of burned areas and enhance post-fire land management practices. Through strategic reforestation efforts with species resilient to fire and conducive to carbon sequestration, the region aims to not only mitigate fire risks but also reinforce biodiversity and ecosystem resilience. Moreover, implementing forest management practices that optimize productivity and sustainability are essential to maintaining the health and vitality of these forests.

These practices may include selective thinning, prescribed burning, and the promotion of mixed species stands to enhance ecosystem resilience and reduce the vulnerability of forests to wildfire. In addition to proactive forest management, educational initiatives targeting residents, visitors, and stakeholders are instrumental in fostering a culture of fire prevention and safety. By raising awareness about the ecological importance of Serra da Estrela's and overall Centro forests and the risks posed by wildfires, communities can become active participants in wildfire prevention efforts. Moreover, empowering local communities with the knowledge and resources to implement fire prevention measures on a grassroots level can significantly reduce fire ignitions and the severity of wildfires. Furthermore, leveraging advances in meteorological forecasting and early warning systems enables authorities to prioritize resources and respond swiftly to extreme fire danger days. By implementing targeted interventions on days with adverse weather conditions, such as increased patrols, enhanced surveillance, and coordinated firefighting efforts, the region can reduce the frequency and severity of wildfires, thereby safeguarding its forests and natural heritage. Overall, adaptation strategies serve as a crucial asset in preserving the forests of Serra da Estrela, ensuring their resilience to the growing threat of forest fires, and securing the long-term sustainability of the region's natural ecosystems and communities.

By integrating insights from forest management, ecology, meteorology and education, communities can build resilience to the growing threat of forest fires and ensure the long-term sustainability of their natural environment and way of life. These insights can be put in place under the three types of strategies that were assessed. One focused only on awareness measures, other on awareness and coercive measures, and the last only on coercive measures. Awareness measures cover initiatives such as continuous education and capacitation of the society. On the other hand, coercive measures encompass actions such as targeted fines. These adaptation measures aim to reduce ignitions and the costs related to large wildfires. For example, Figure 2.41 shows the projected losses without adaptation (black bar) and with implementation of adaptation measures (blue, green, and orange bars), in million euros/year for Centro. Focusing on RCP4.5, the 85 million euros/year mean value may reach 163 million euros/year under climate change, which means an increment of 78 million euros/year.

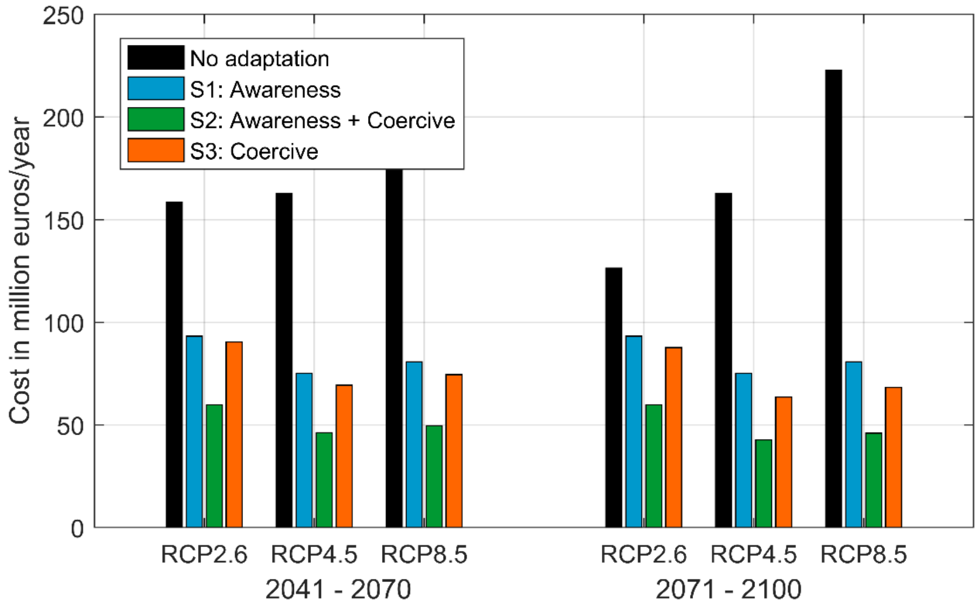


Figure 2.41 – Projected cost of no adaptation (black bar) and cost with implementation of adaptation strategies of Awareness (blue bars), Awareness + Coercive (green bars), and Coercive (orange bars), in million euros/year for Centro, under RCP2.6, RCP4.5, and RCP8.5 for the middle of the century (2041 – 2070; left) and the end of the century (2071 – 2100; right).

With a strategy focused on awareness, it is possible to reduce the losses to about 75 million euros/year. It is however important to note that with the advancement of time, climate change will severely impact the number of days in extreme danger, and consequently coercive strategies to reduce the number of ignitions and consequently burned area may be used. These strategies can represent savings of 88 million euros/year. However, it is essential to note that a pathway focused on both awareness and coercive strategies brings better results, to about 45 million euros/year, representing savings of the order of around 40 million euros/year when compared to the historical values, and of about 100 million euros/year to the no adaptation pathway. Figure 2.42 shows the adaptation pathway for Centro focused on RCP4.5. Several adaptation and mitigation strategies were already implemented and are expected to continue being implemented in the coming years. Awareness strategies should be first implemented to alert and educate society to the perils of climate change and its impact on forest fires. Eventually, in the most dangerous periods, coercive strategies should be implemented. However, with the increase in global warming, a mix between awareness and coercive continuous strategies must be implemented to prevent tragedies such as the 2022 Serra da Estrela or 2017 Pedrógão Grande fires to become the new normal.

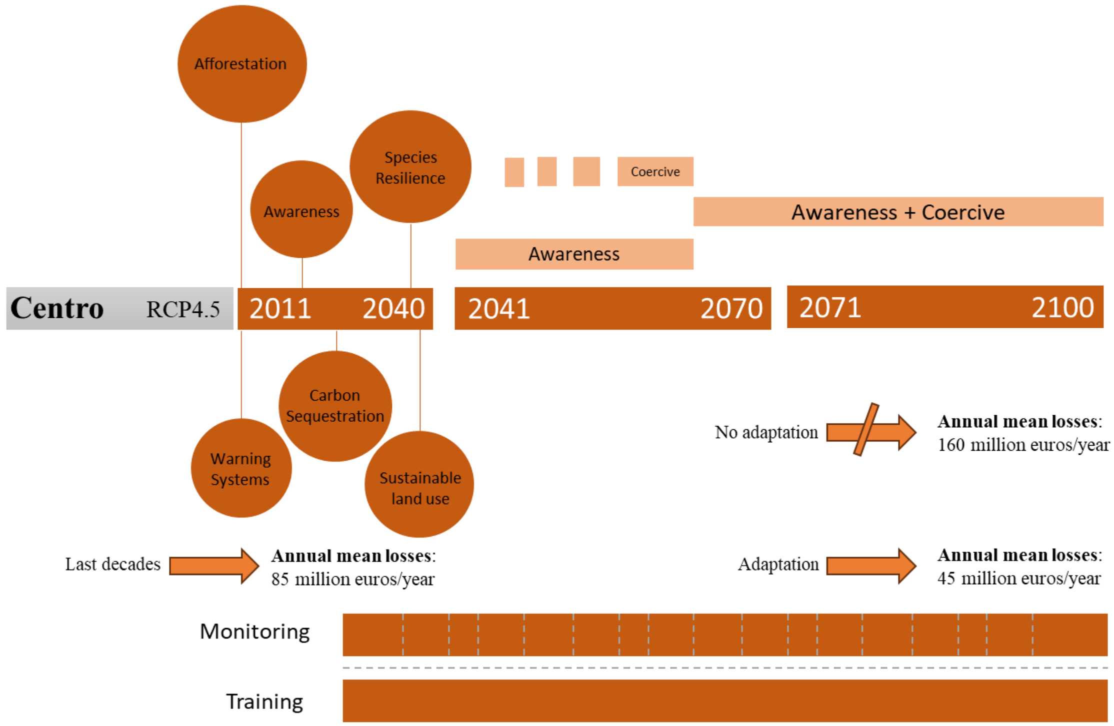


Figure 2.42 – Adaptation narrative for forest fires sector until 2100 for Centro under RCP4.5.

2.3. Área Metropolitana de Lisboa

2.3.1. Climate projections

Projections indicate a more pronounced warming in summer than in winter across all climate scenarios for the A.M.Lisboa region. In the RCP4.5 scenario, the A.M.Lisboa region is projected to undergo a temperature rise of 1.7 – 2.3 ºC (Figure 2.43 and Table 2.27). Even under the RCP2.6 scenario, an increase in annual temperature of 1.3 ºC is expected during the 21st century. Conversely, under the RCP8.5 scenario, temperature increases of +3.8 ºC and +4.1 ºC are foreseen by the end of the 21st century respectively, for maximum and minimum temperatures.

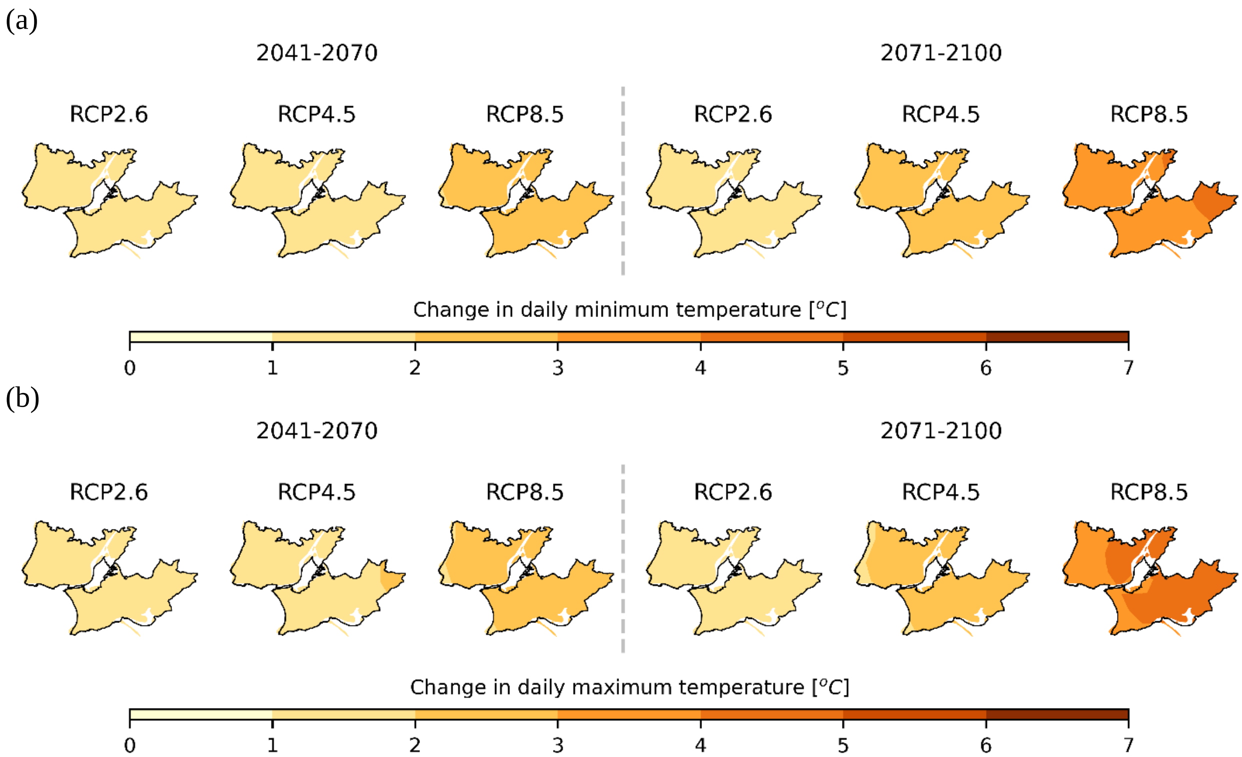


Figure 2.43 – Future projected changes in daily (a) minimum and (b) maximum temperature (ºC) for the A.M.Lisboa NUTS II region.

Table 2.27 – Climatological annual mean daily minimum (Tn) and maximum (Tx) temperature (ºC) for the reference period (Historical – 1971-2000); and, future projected changes in daily minimum and maximum temperature (ºC) for the A.M.Lisboa NUTS II region.

A.M.Lisboa	1971-2000	Differences	2041-2070			2071-2100		
	Historical		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
T_n (°C)	11.2	ΔT_n (°C)	1.3	1.7	2.2	1.3	2.2	3.8
T_x (°C)	20.5	ΔT_x (°C)	1.3	1.8	2.4	1.2	2.3	4.1

Changes in precipitation are greatly dependent on the season and the future emission scenario. Future projections suggest a decline in mean precipitation across the 21st century under RCP4.5 and RCP8.5, and a small increase under RCP2.6 scenario (Figure 2.44 and Table 2.28). The RCP4.5 scenario portrays a decline in annual precipitation, with projected reductions of around -10% by the end of the 21st century. For the RCP2.6 scenario, the precipitation changes are small, fluctuating around +3%. For the RCP8.5 scenario, the projections point to an annual decrease exceeding -15% and -25% by the mid- and end- of the century, respectively.

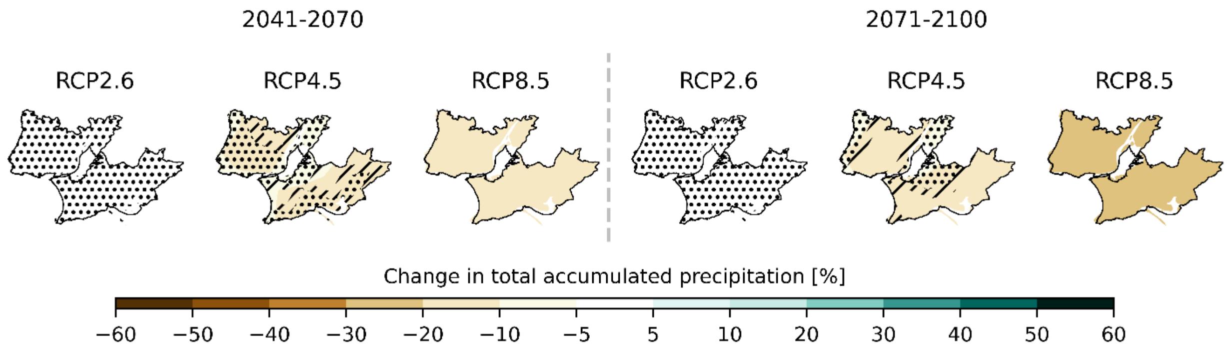


Figure 2.44 – Future projected relative changes in annual accumulated precipitation (%) for the A.M.Lisboa NUTS II region. Grid-points where the precipitation does not specify changes statistically significant are identified by dotted hatching.

Table 2.28 – Climatological annual mean accumulated precipitation (Pr) (mm) for the reference period (Historical – 1971-2000); and, future projected relative/absolute changes in annual accumulated precipitation (%/mm) for the A.M.Lisboa NUTS II region.

A.M.Lisboa	1971-2000 Historical	Differences	2041-2070 RCP2.6	2041-2070 RCP4.5	2041-2070 RCP8.5	2071-2100 RCP2.6	2071-2100 RCP4.5	2071-2100 RCP8.5
$Pr\ (mm)$	751.2	ΔPr (%)	2.2	-10.3	-16.8	3.7	-11.2	-28.1
		$\Delta Pr\ (mm)$	16.6	-75.0	-122.8	29.5	-85.0	-206.1

As a result of the warming, the frequency and intensity of extreme temperature events will undergo changes, which are less (more) pronounced under the RCP2.6 (RCP8.5) scenario (Figure 2.45). Concurrent with the rise in maximum temperatures, the occurrence of hot days[37], as well as summer[38] and extremely hot days[39], is projected to escalate. In the historical period (1971-2000), the number of hot days ranges between 0 and 60 days from littoral to inland. For the RCP4.5, more 25 hot days are expected at the end of the century. For the RCP2.6, the increase is around 16 days, but for the RCP8.5 the number of hot days is projected to increase around 55 days with respect to the historical period. Furthermore, heatwaves[40] are projected to

[37] Hot days: number of days where maximum temperature exceeds 30ºC.
[38] Summer days: number of days where maximum temperature exceeds 25ºC.
[39] Very hot days: number of days where maximum temperature exceeds 35ºC.
[40] Heatwave is defined as a period of five or more consecutive days with maximum temperature above the 90th percentile.

become more frequent, intense, and longer lasting. In the historical period approximately 1 to 2 heatwaves occur per year with a mean duration around 6 days per event. Under the RCP4.5, it is expected an increase in the number of heatwaves between 3 and 4 throughout the 21st century. Even under the RCP2.6, the occurrence of more 2 heatwaves per year is projected. However, considering the RCP8.5, the projections point to more 7 heatwaves per year. Aligned with the increase in the number of heatwaves, the mean duration of these events is also projected to increase. For the RCP4.5, the mean duration of heatwaves is projected to increase around 2 days. A similar result is expected for the RCP2.6, whilst under the RCP8.5, the expected increase is between 3 and 4 more days in heatwave, when compared with the historical period. Aligned with the rising of minimum temperature, tropical nights[41] are expected to become more prevalent, while the incidence of cold days[42] will diminish. For the RCP4.5 the number of tropical nights is projected to increase up to more 50 nights per year, and for the RCP8.5 the projected changes may reach up to more 90 nights per year.

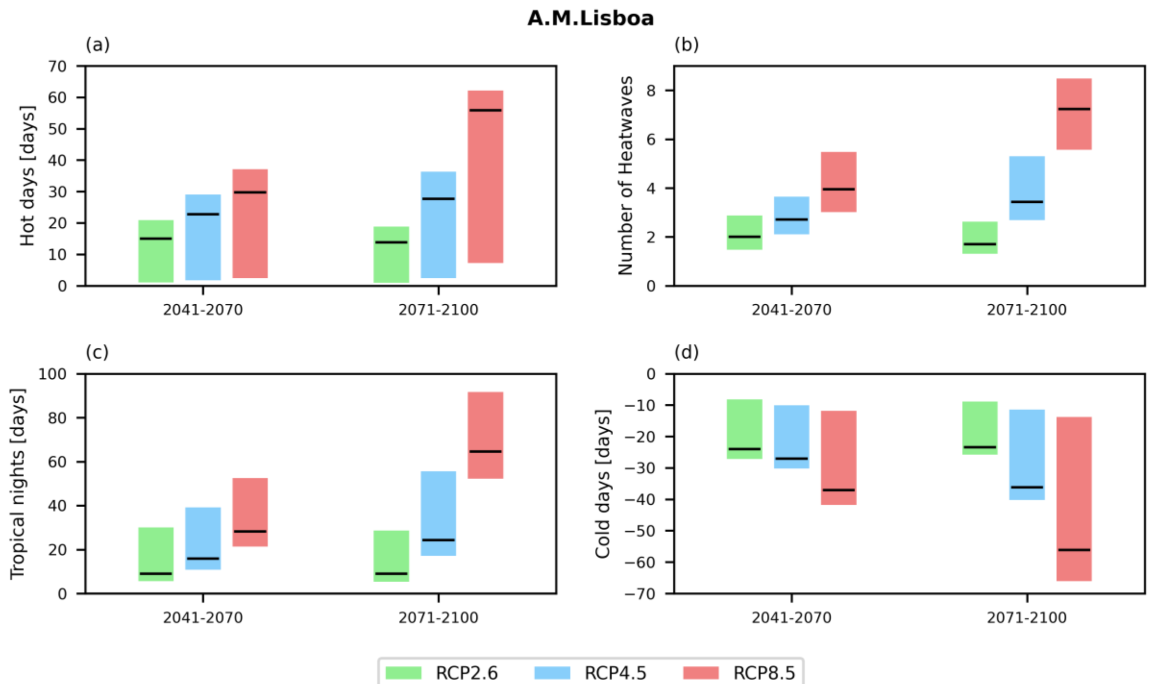


Figure 2.45 – Distribution of the projected changes in (a) hot days [days/year], (b) number of heatwaves per year, (c) tropical nights [days/year] and (d) cold days [days/year] for all gridpoints in A.M.Lisboa's region. The straight black line represents the mean value for the A.M.Lisboa's region. Individual boxes span from the spatial minimum to the maximum value of the A.M.Lisboa's region.

In line with the decline in mean accumulated precipitation, a reduction in the number of wet days[43] and, consequently, an increase in the number of dry days, is projected until the end of the 21st century (Figure

[41] Tropical nights: number of days where minimum temperature exceeds 20ºC.
[42] Cold days: number of days where minimum temperature is below 7ºC.
[43] Wet days: number of days with precipitation exceeding 1 mm/day.

2.46). For the RCP4.5 scenario, less 10 wet days is projected throughout the 21st century. For the RCP2.6 scenario, however, negligible changes are projected throughout the century, with a slight decrease during the mid- and end-21st century around 2 wet days. For the RCP8.5 scenario, the projections point to less 26 wet days at the end of the 21st century with respect to the historical period. The number of consecutive dry days[44] is expected to increase, enhancing drying conditions. Regarding the number of days with moderate[45] and heavy[46] precipitation, clear projected reductions are evident, especially under the RCP4.5 and RCP8.5 scenarios. The maximum 5-day accumulated precipitation[47] is projected to increase for the RCP4.5 and RCP8.5 scenarios. Under the RCP4.5 scenario, the increases can reach more 50 mm (in the historical period the MaxPr5d value is around 200 mm). The results for the RCP2.6 scenario are rather heterogeneous with similar positive and negative changes. For the RCP8.5 scenario, the increase of maximum 5-day accumulated precipitation can reach more 40 mm. In spite of the projected decrease of the number of wet days, projections suggest a concentration of rainfall into shorter time frames, implying an intensification of moderate/heavy precipitation regardless of the scenario.

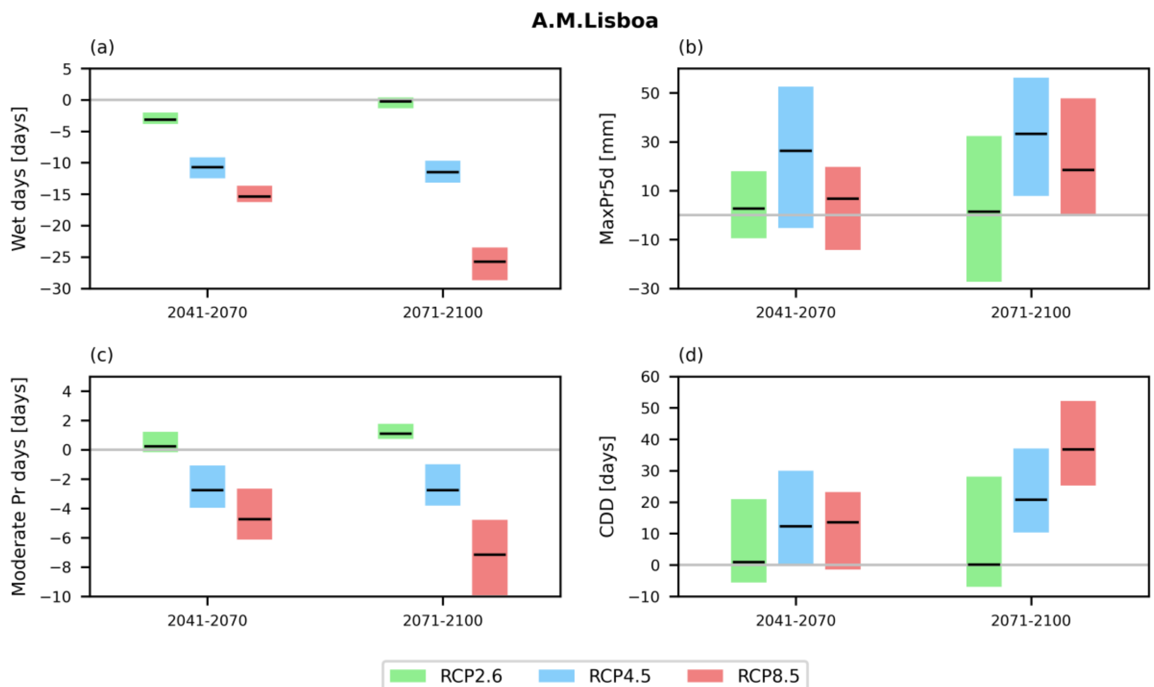


Figure 2.46 – Distribution of the projected changes in (a) wet days [days/year], (b) maximum of 5-day accumulated precipitation (MaxPr5d) [mm], (c) moderate precipitation days [days/year] and (d) consecutive dry days (CDD) [days] for all gridpoints in A.M.Lisboa's region. The straight black line represents the mean value for the A.M.Lisboa's region. Individual boxes span from the spatial minimum to the maximum value of the A.M.Lisboa's region.

[44] Dry days: number of maximum consecutive dry days where precipitation is below 1 mm/day.
[45] Moderate precipitation days: number of days with precipitation exceeding 10 mm/day.
[46] Heavy precipitation days: number of days with precipitation exceeding 20 mm/day.
[47] Maximum of 5-day accumulated precipitation.

A summary of confidence in the direction of projected changes in climate means and indices is presented in Table 2.29. The results give us confidence in climate projections presented here.

Table 2.29 – Summary of confidence in direction of projected change in climate means and indices for the A.M.Lisboa NUTS II region. Temperature: climatological annual mean daily minimum (Tn) and maximum (Tx) temperature, hot days (Txg30), number of heatwaves per year (HWN), tropical nights (Tng20) and cold days (Tnl7); Precipitation: climatological annual mean accumulated precipitation (Pr), wet days (Prg1), maximum of 5-day accumulated precipitation (MaxPr5d), moderate precipitation days (Prg10) and consecutive dry days (CDD). A standard deviation of 0.25, 1, 2, 3 corresponds to a moderate, strong, very strong, severe increase/decrease of the variables. Values shown are ensemble median changes. Colours illustrate the model's agreement within the multi-model ensemble.

A.M.Lisboa							
		2041-2070			2071-2100		
		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Temperature	Tx	↑↑	↑↑↑	↑↑↑	↑↑	↑↑↑	↑↑↑
	Txg30	↑	↑↑	↑↑	↑	↑↑	↑↑↑
	HWN	↑	↑↑	↑↑↑	↑	↑↑	↑↑↑
	Tn	↑↑	↑↑↑	↑↑↑	↑↑	↑↑↑	↑↑↑
	Tnl7	↓	↓↓	↓↓	↓	↓↓	↓↓↓
	Tng20	↑	↑↑↑	↑↑↑	↑	↑↑↑	↑↑↑
Precipitation	Pr	⊠	↘	↘	⊠	↘	↘
	MaxPr5d	⊠	↗	⊠	⊠	↑	↗
	Prg1	⊠	↘	↘	⊠	↘	↓
	Prg10	⊠	↘	↘	⊠	↘	↘
	CDD	⊠	↗	↗	⊠	↗	↑

↑↑↑	Change above 3 standard deviations
↑↑	Change above 2 standard deviations
↑	Change above 1 standard deviation
↗	Change above 0.25 standard deviations
⊠	Change between -0.25 and 0.25 standard deviations
↘	Change below -0.25 standard deviations
↓	Change below -1 standard deviation
↓↓	Change below -2 standard deviations
↓↓↓	Change below -3 standard deviations

(dark green)	High agreement: at least 80% of models show a positive change
(light green)	Low agreement: at least 50% of models show a positive change
(grey)	No agreement: models disagree on the direction of change
(light blue)	Low agreement: at least 50% of models show a negative change
(dark blue)	High agreement: at least 80% of models show a negative change

2.3.2. Water scarcity and stress on crops

NUTS II Área Metropolitana de Lisboa includes, within its administrative boundaries, two River Basins, where RH5 – Tejo e Ribeiras do Oeste stand out (Figure 2.47). This region comprises two hydro-agricultural developments, the Lezíria Grande de Vila Franca de Xira and the one in Loures.

Figure 2.47 – NUTSII Área Metropolitana de Lisboa and River Basins location: RH5 – Tejo e Ribeiras do Oeste and RH6 Sado.

In 2022, the Área Metropolitana de Lisboa region was the leading national producer of main crops for industry, and potato, contributing with 47.4% and 23.8%, respectively, to the country's total production in these crops. In this region, is processing tomatoes, accounting for a 54.8%, followed by maize production with 13.7% of the region's total productivity.

Considering the full area of River Basin RH5, Tejo e Ribeiras do Oeste, climate change scenario projections indicate a decrease in water yield for the RCP4.5 scenario, for the period 2071-2100 (Figure 2.48). The trend of decreasing water yield becomes more pronounced for the scenario with higher concentrations of greenhouse gases in the atmosphere (RCP8.5). However, if concentration levels follow those outlined in the Paris Agreement throughout the 21st century (RCP2.6), the projections from the mid-century onwards show no particular significance for the water yield, projecting even a slight improvement. Nevertheless, it is essential to emphasize that this does not necessarily imply a reduction in water stress levels within the region. The dynamics of water stress depend on balancing water availability with demands. The Water Exploitation Index plus (WEI+) is a ratio comparing water use to renewable water resources and serves as a common tool in the European Union and Portugal for assessing this equilibrium.

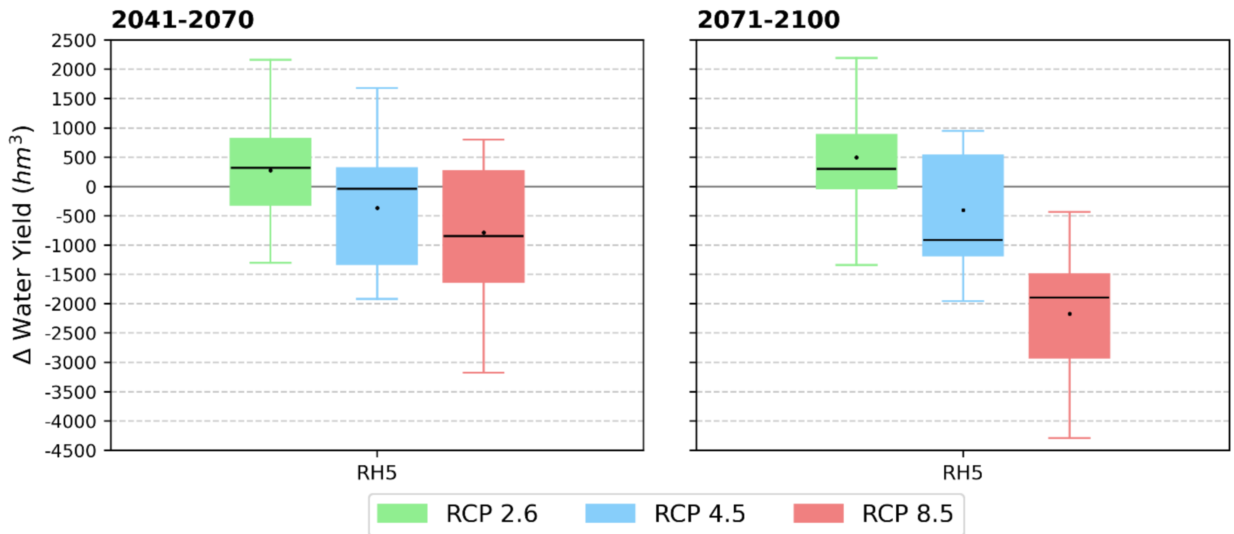


Figure 2.48 – Projected changes in averaged water yield (hm^3) for River Basin RH5 Tejo e Ribeiras do Oeste. Two future periods are shown: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5 and RCP8.5. The black line represents the ensemble median.

The Water Exploitation Index plus for the River Basin RH5, Tejo e Ribeiras do Oeste is presented in Figure 2.49. Under the RCP4.5 scenario, a slight increase of around 2 percentage points could be expected. Conversely, the RCP8.5 scenario exhibits a clearer trend, indicating an increase in WEI+, with the highest value approaching an additional 12 percentage points for the period 2071-2100. Regarding the RCP2.6 scenario, the projected changes show no significant difference when compared with the historical situation.

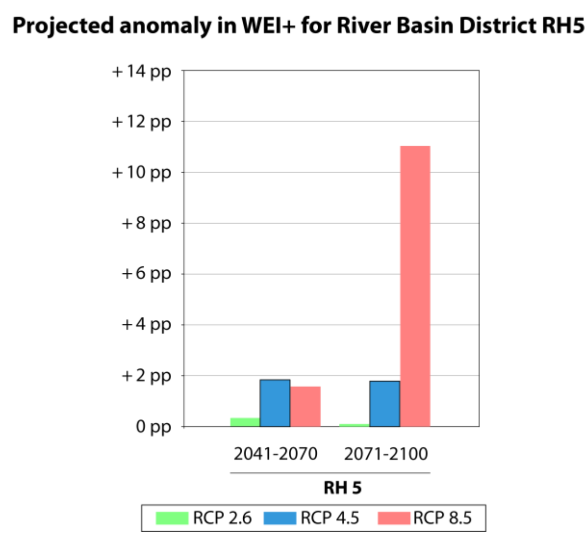


Figure 2.49 – Projected change in WEI+ (in percentage points) for River Basin RH5 Tejo e Ribeiras do Oeste. Two future periods are shown: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5 and RCP8.5. The presented values refer to the ensemble median.

Climate change can affect both irrigation requirements and productivity of the main crops grown in mainland Portugal. Table 2.30 illustrates these impacts on four crops: tomato for industry, corn, potato, and olive grove, representing 54.8%, 17%, 5.6% and 0.3% of the crop's productivity considered in NUTS II Metropolitan Area of Lisbon. For olive groves, relative stability is observed across various climate change scenarios. However, a trend of decreasing productivity is noted for tomato, corn, and potato, which could lead to a production decrease of up to -9%, -14% and -24%, respectively, in RCP4.5, compared to current productivity levels.

Considering all costs and benefits due to climate change in crops, the overall economic losses can amount to more than 29 million euros per year for the time frame 2041-2070 and more than 27 million euros for the period 2071-2100 in RCP4.5. Economic losses in productivity are related to modifications in climatic conditions for the crops currently developed in the region due to changes in plant phenology.

Table 2.30 – Projected changes in productivity in average % for tomato, corn, potato, and olive grove in NUT II Área Metropolitana de Lisboa for two future periods: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5 and RCP8.5. The presented values refer to the ensemble median.

NUTS II AML	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Tomato	-5.5%	-9.1%	-10.4%	-6.9%	-8.9%	-14.3%
Corn	-7.3%	-10.4%	-13.3%	-5.7%	-14%	-20.8%
Potato	-14.2%	20.1%	-24.3%	-14.1%	-24.3%	-33.7%
Olive grove	-0.1%	-0.5%	-0.9%	-0.2%	-0.5%	-1.2%

To adapt the NUTS II Área Metropolitana de Lisboa to the projected impacts of climate change on water and agroforestry sectors, it is suggested that initial measures to be implemented should be of the no-regrets type. Specifically, this involves promoting the reduction of losses in the distribution network in hydro-agricultural developments and increasing irrigation efficiency throughout the region. Currently, hydro-agricultural developments in Loures and Lezíria Grande de Vila Franca de Xira report losses of 40% and 28.7% in the distribution network, respectively. This proposal recommends that all irrigation perimeters achieve distribution network efficiency levels around 90%.

In terms of irrigation efficiency, significant progress has been made in recent years, but there is still room for improvement. it is assessed that all irrigation in applicable crops transition to using drip irrigation systems, where irrigation efficiency typically ranges between 90-95%. Additionally, it is advisable to consider reducing water losses in the distribution network for urban purposes. Although the overall average of losses is currently reported to be around 14% for the entire NUTS II region, some water managing entities have losses exceeding 25%.

In this region, the implementation of water reuse is of particular importance (a no-regrets measure) due to the high urban density of the area and, as a consequence, the significant amount of potentially available water in this regard.

Subsequently, the simulations include a win-win measure that consists of the implementation of techniques promoting greater water retention in the soil (e.g., direct seeding, mulching) and the creation of water retention landscapes (e.g., creating ponds, planting in valleys and berms). This can contribute to a longer maintenance of the balance between water supply and demand in NUTS II through transformative adaptation.

It is also crucial to ensure the success of the suggested adaptation actions by raising awareness and providing training to farmers. Farmer training should cover adaptive agricultural practices to help them cope with changing conditions, including the implementation of water management techniques, the introduction of drought-resistant crops, and the adjustment of planting and harvesting schedules. In this context, it is worth noting that the impacts of climate change will affect not only water availability but also agricultural productivity. Even if all plant water and nutrient needs are met, productivity losses will occur in scenarios with higher greenhouse gas emissions/concentrations over the century due to changes in plant phenology.

Adaptation in RH5 Tejo e Ribeiras do Oeste[48]

In economic terms, the projected impacts of climate change on water availability for RH5 could result in losses averaging up to 32 thousand euros per year in RCP4.5 for the time frame 2041-2070 and more than 793 thousand euros for the period 2071-2100. Considering other scenarios, gains can vary on average up to 276 thousand euros (RCP2.6 period 2041-2070), while losses can be as high as 1.6 million euros on average per year (RCP8.5 period 2071-2100).

In this River Basin, a decrease in the average annual volume stored in the reservoirs is projected, with values that can reach more than -3% in the RCP4.5 scenario (Table 2.21). This situation is more pronounced in the RCP8.5 scenario, where the decrease could reach -9% by the end of the century. For the RCP2.6

[48] For the adaptation in RH6, please refer to the Adaptation storyline for NUTS II Alentejo.

scenario, it is projected that there will be a slight decrease in average stored volumes, but it is not considered significant.

Table 2.31 – Projected changes in average annual volume stored in reservoirs in % for RH5, considering two future periods (anomaly) 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. The presented values refer to the ensemble median.

River Basins (RH5)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Reservoirs Availability	-1.6%	-3.5%	-2.7%	-1.4%	-2.9%	-9.0%

With the implementation of the above-mentioned adaptation measures for RH5, the identified economic impacts could be minimized in these river basins, and some benefits would be achieved. Table 2.32 shows the overall results for RH6 with the percentual changes to the Water Exploitation Index Plus (WEI+) with the implementation of each of the following adaptation measures: reducing system water loss and leakages, improving irrigation efficiency, selection of crops better suited to climate change projections, and wastewater recycling and reuse.

Table 2.32 – Projected change in WEI+ (in percentage points) for RH5 are shown considering two future periods: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. The presented anomalies refer to the ensemble median and consider the following factors: no adaptation, the reduction of system water loss and leakages, the improvement of irrigation efficiency, the selection of crops better suited to climate change projections, and wastewater recycling and reuse.

River Basins (RH5)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Climate change impacts (no adaptation)	+0.69 pp	+1.82 pp	+1.60 pp	+0.10 pp	+1.80 pp	+11.04 pp
Reducing system water loss and leakages	+0.46 pp	+1.45 pp	+1.36 pp	-0.24 pp	+1.52 pp	+10.00 pp
Improving irrigation efficiency (entails reducing system water loss and leakages simultaneously)	-0.39 pp	+0.98 pp	+0.90 pp	-0.95 pp	+0.94 pp	+8.22 pp
Changing current irrigated crops (entails reducing system water loss and leakages simultaneously)	-1.57 pp	+0.12 pp	+0.08 pp	-2.02 pp	-0.52 pp	+4.97 pp
Wastewater for reuse (entails reducing system water loss and leakages simultaneously)	-3.95 pp	-2.40 pp	-2.38 pp	-4.23 pp	-2.61 pp	+0.31 pp

All the individually modelled measures contribute to benefiting the region by reducing the disparities between the projected and the scenario of no adaptation. The measure that brings the most benefits to the region, among those that were modelled, involves wastewater recycling and reuse in combination with reducing system water loss and leakages on hydro-agricultural developments. In this case the anomaly in WEI+ can be reduced by up to 10 percentage points at the end of the century. It is noteworthy that this measure can neutralize the impacts of climate changes on water balance or even improve the current situation, with the exception of RCP8.5 at the end of the century.

Since not all discusses measures were modelled, the prioritization of all adaptation measures for RH5 is presented in Figure 2.50. The figure outlines the timeline for the full implementation of each measure aimed at mitigating the projected impacts of climate change. The proposed timeframe may be subject to change based on ongoing monitoring of the impacts of climate change, aiming to implement adaptive management over time.

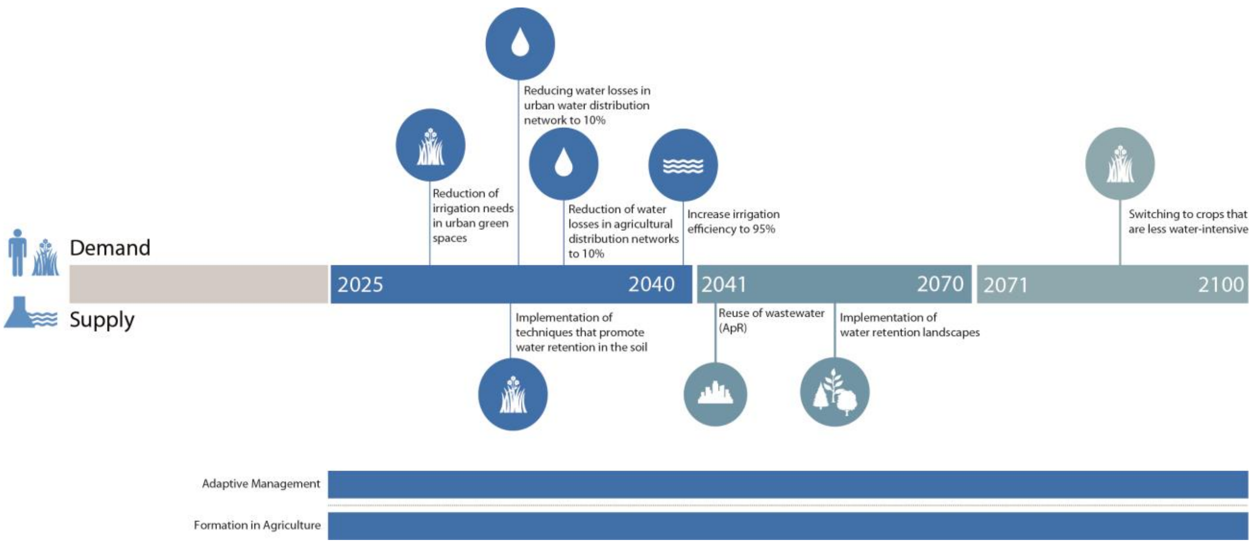


Figure 2.50 – Adaptation narrative for the water resources and agroforestry sectors in RH5 until 2100.

2.3.3. Coastal flooding

Área Metropolitana de Lisboa is the most urbanized and densely populated NUTSII sub-section, particularly vulnerable to the impacts of rising sea levels and changes in wave climate patterns (the reader is referred to the WP4.5/6 dynamic modelling report). This area is characterized by about 120 km of ocean-facing coastlines, housing different coastal environments (Figure 2.51), namely long sandy beaches (*e.g.*, São João da Caparica, Fonte da Telha), sandy beaches with adherent structures (*e.g.*, Costa da Caparica seawall, Carcavelos seawall, among others), pocketed beaches and rocky cliffs (*e.g.*, from Ericeira to Sintra, and from Meco to Setúbal) and urban beaches (*e.g.*, Cascais, Estoril, Parede, Carcavelos, Caxias, Algés). The inland waters of the Tagus River estuary face most of the Portuguese capital, Lisbon, as well as other low-lying areas, especially to the East and Southeast of the city. Other smaller-scale interesting features include the Jamor, Trancão and Sorraia River mouths, largely artificialized throughout their extension, and the Albufeira coastal lagoon.

Figure 2.51 – The Área Metropolitana de Lisboa NUTSII region, depicting the most relevant locations in terms of projected coastal vulnerability.

The vulnerability assessment carried for the Área Metropolitana de Lisboa revealed that the coastlines facing inland waters are projected to be more threatened to climate change, in comparison to the ocean-facing ones, mostly due to the large extension of low-lying areas surrounding the Tagus River estuary, in comparison mostly rocky coastlines elsewhere (Figure 2.52). Highly vulnerable inland waters dominate the assessment conducted for the region, as soon as by the mid-21st century, and under a moderate concentrations' scenario (RCP4.5). A worsening of the vulnerability conditions is expected to occur towards the end of the 21st century for all considered scenarios. Note that relevant urbanized areas are projected to be threatened by changes in the total water levels[49], such as Vila Franca de Xira, Alhandra, Alverca, Cacilhas, Seixal, Barreiro, Lavradio, Baixa da Banheira, Moita, Montijo, Alcochete, among others, for values associated to return periods as short as 4 years. The lowest areas of the capital city of Lisbon are

[49] The total water level (TWL) is given by the sum of the sea level rise (SLR), tide and storm surge components. For the ocean-facing coastlines, the run-up associated with a 99th percentile energy wave event is also considered.

also expected to become highly vulnerable, with the zones of Marvila, Cais do Sodré, Alcântara, Belém and Cruz Quebrada being the ones projected to be more severely affected. Considering the sandy ocean-facing coastlines, the non-urbanized areas of Costa da Caparica (especially at São João da Caparica) and Fonte da Telha show moderate to high vulnerability for all future periods and scenarios.

Considering the Área Metropolitana de Lisboa region as a whole, and for the three classes of vulnerability adopted (low, medium and high, associated to the 100-, 25- and 4-year total water level return values) projections revealed 3.0-3.4 km² of vulnerable ocean-facing coastlines (beaches), and 207.0-218.2 km² of vulnerable coastlines facing inland waters (mostly in the Tagus River estuary; Table 2.33), depending on the future period and scenario. Departing from the intermediate RCP4.5 scenario, on a trajectory closer to the RCP8.5, an increase up to 4.2 km² in the vulnerable areas of Área Metropolitana de Lisboa is projected by 2100.

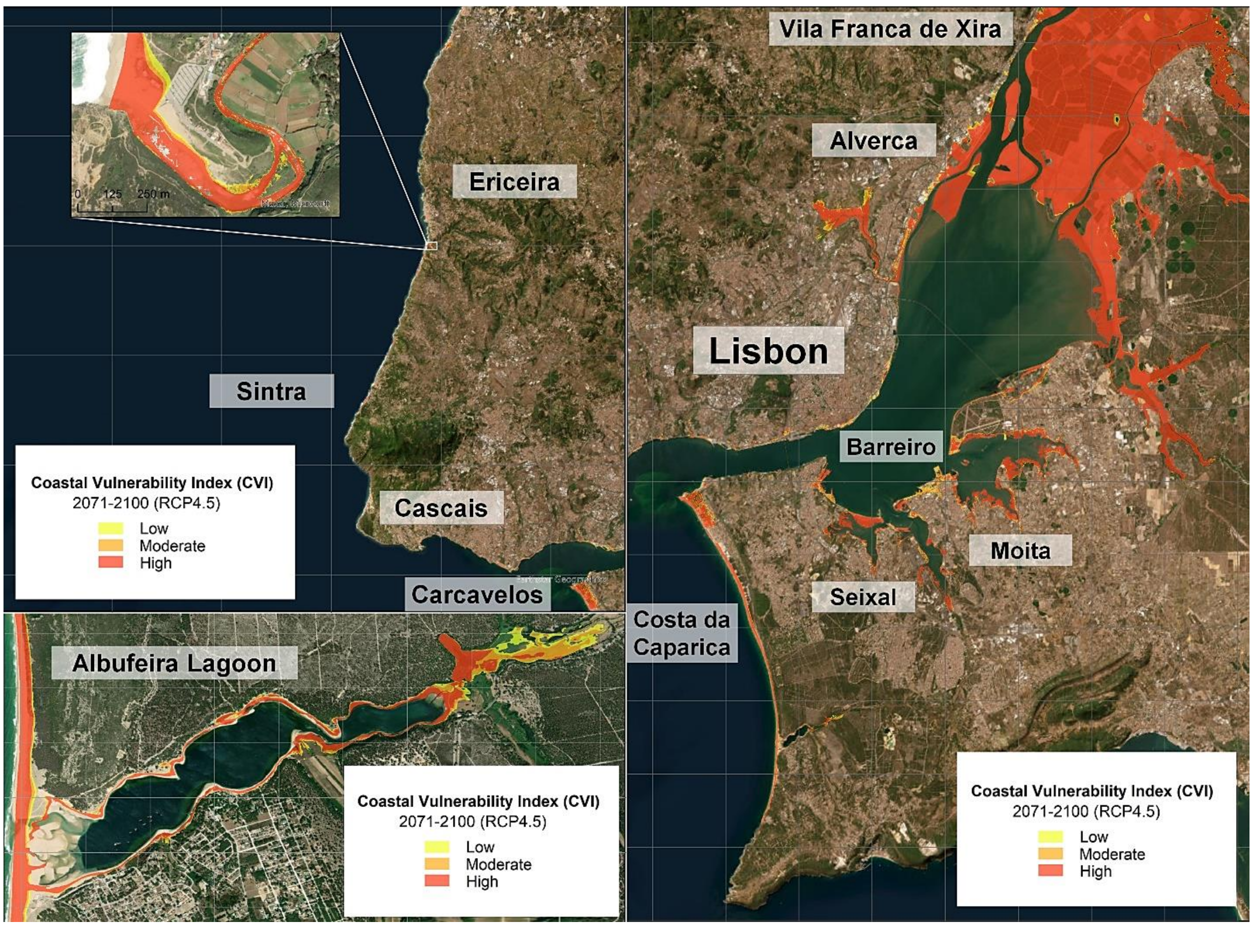


Figure 2.52 – Projected vulnerable areas along three coastal stretches of Área Metropolitana de Lisboa region (Mafra to Oeiras, and Oeiras to Vila Franca de Xira and Alcochete to Sesimbra) by the end of the 21st century (2071-2100) under RCP4.5, highlighting the Albufeira coastal lagoon. The CVI is inversely related to the TWL 4-, 25- and 100-years return period values (*e.g.*, a high CVI is given to coastal areas projected to become flooded under a 4-year RP TWL).

Table 2.33 – Area (in km²) of the vulnerable coastal stretches in the Área Metropolitana de Lisboa region (grouped for the three classes of vulnerability), by the end of the 2041-2070 and 2071-2100 future periods, under both RCP4.5 and RCP8.5 scenarios.

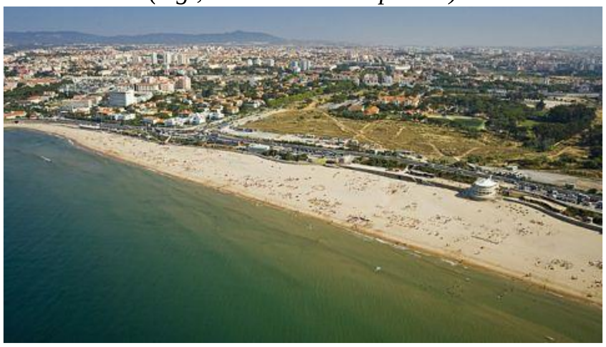
Vulnerable coastal areas (km²)				
Área Metropolitana de Lisboa	2041-2070		2071-2100	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Ocean-facing	3.0	3.0	3.4	3.0
Inland	207.0	209.7	213.6	218.2
Total	210.0	212.7	217.0	221.2

Considering the diverse coastal environments in Área Metropolitana de Lisboa, a single common adaptation narrative is not feasible, and different narratives have to be built (one for each coastal typology). Figure 2.57 shows, similarly to Figure 2.17 and Figure 2.37, the proposed adaptation pathways along the five identified environments. For each one, different pathways are shown, spanning from the present time until the end of the 21st century, and varying due to: (1) each coastal environment's expected response to changes in total water levels and wave characteristics (if facing the ocean), (2) the different possibilities in terms of adaptation strategies, and (3) any site-specific adaptation effort that was already carried in the recent past.

Sandy beaches with adherent structures
(e.g., Costa da Caparica)

Low-lying sandy beaches
(e.g., São João da Caparica)

Pocket beaches and rocky cliffs
(e.g., Ericeira – Praia dos Pescadores)



Urban beaches
(e.g., Carcavelos)

Inland waters
(e.g., Tagus River estuary)

Figure 2.53 – Different coastal environments in the Área Metropolitana de Lisboa NUTSII region. Specific adaptation pathways are built for each environment in Figure 2.57.

It should be highlighted that approximately 20% of Área Metropolitana de Lisboa's coastlines correspond to either urban beaches or sandy beaches with adherent structures, revealing extensive coastal anthropization (Figure 2.53). Therefore, protection and accommodation measures are key to increase local resiliency in a timely and effective manner. Artificial beach nourishment has been one of the prioritized protection measures in the current national-scale adaptation strategy (Pinto et al., 2020), and should continue to be applied consistently in several specific locations throughout Área Metropolitana de Lisboa. It should be noted, nevertheless, that such interventions are usually quite localized and may vary greatly in terms of frequency and intensity even within the same coastal environment. Across Área Metropolitana de Lisboa, artificial beach nourishment has been extensively used in Costa da Caparica, Carcavelos, and other urban beaches near Cascais, totalizing more than 4.6 million cubic meters since 2005 (Figure 2.55). Its application varies greatly, however, even within the same coastal environment, since local conditions may hinder its overall effectiveness, or transportation costs might be too high to justify such an approach. Such occurrences are, nevertheless, uncommon, especially due to the relatively small extension of the area, and the existence of borrow sites at the entrance of the Tagus River estuary ("Barra Sul" Channel), and therefore, artificial nourishment is considered as the most viable adaptation measure along urban and pocketed beaches, and beaches with adherent structures, at least until the end of the first half of the 21st century (Figure 2.57).

The accommodation of the adherent structures (such as seawalls, tidal dykes and harbour structures; Figure 2.57) is considered a viable option protect the urbanized areas not only along the ocean-facing coastlines but also the ones facing inland waters. Such measure is projected to become increasingly relevant after the middle of the 21st century. Long-term SLR-induced shoreline retreat is projected not only to deem artificial nourishments ineffective, given the permanent flooding of pre-existing beaches at the base of the adherent structures (as it was shown for Costa da Caparica in the WP4.5/6 dynamic modelling report), but also to present ever-greater threats to the low-lying areas surrounding the Tagus River estuary. The required topographic height (relative to the National Vertical Datum CASCAIS1938) for the coastal protection structures to withstand the future projected extreme coastal events[50] is set at 8.40 m, under the intermediate RCP4.5 scenario (Figure 2.54), for the analysis conducted at Costa da Caparica. Excluding wave action, the required height for inland waters coastal protection structures is set at 3.11 m, in order to sustain a 100-year return period event by the end of the 21st century. Departing from the RCP4.5, on a trajectory closer to the RCP8.5, an increase of up to 0.10 m (3.11 m → 3.21 m) is expected for the structures' heights facing inland waters, and an increase of up to 0.47 m (8.40 m → 8.87 m) is expected for the ocean-facing ones. These values should be considered as references to all ocean-facing and inland waters coastlines of the Área Metropolitana de Lisboa region. Note, nevertheless, that coastal stretches with steeper slopes, usually present at highly anthropized ocean-facing segments (*e.g.,* urban beaches between Lisbon and Cascais), may expect higher run-up values.

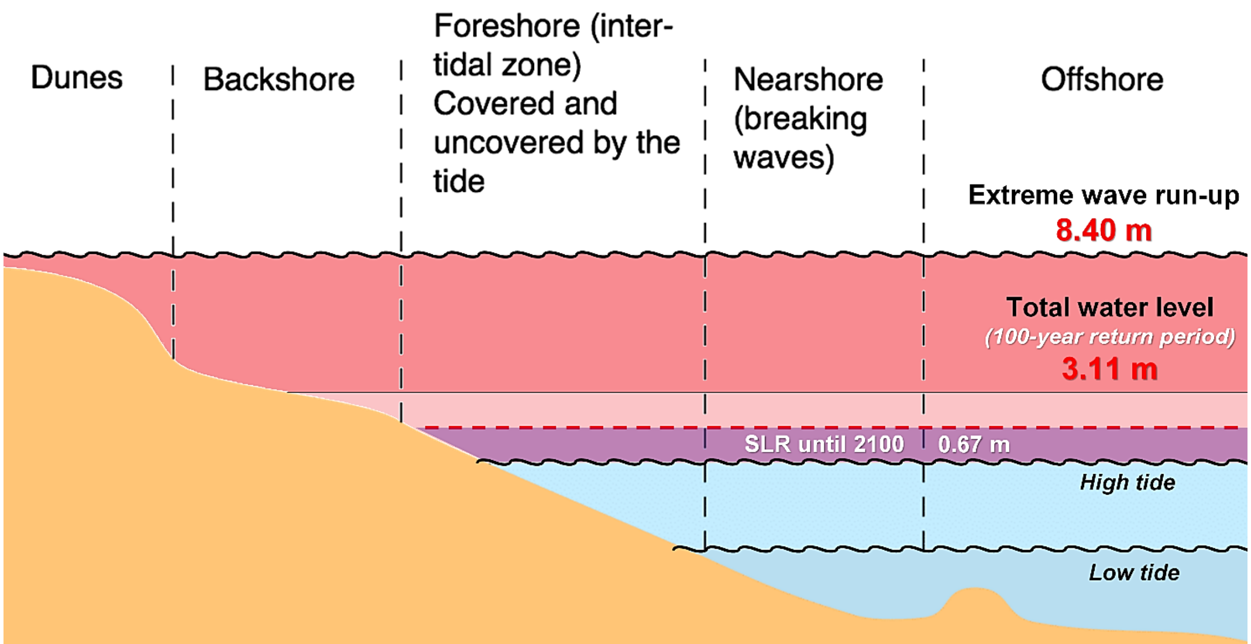


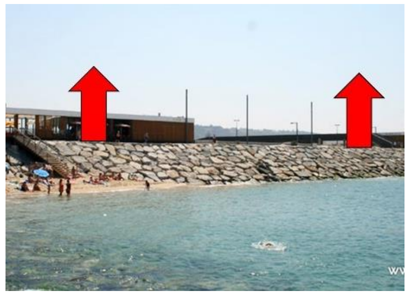
Figure 2.54 – Schematic depiction of how changes in total water levels and run-up may lead to coastal flooding. Note that while for inland waters the maximum coastal flooding topographic height is projected to be set at 3.11 m, for ocean-facing coastlines the value is projected to be set at 8.40 m (values for the RCP4.5 scenario by the end of the 21st century).

While accommodation may still be a viable option towards the end of the 21st century, planned relocation actions (Figure 2.55) should become the most cost-effective way to deal with continuously rising sea levels and extreme coastal flooding along several Área Metropolitana de Lisboa's coastal environments (Figure 2.57), especially in the low-lying areas surrounding the Tagus River estuary. Exceptions are the rocky cliffs and pocket beaches of the Mafra, Sintra, Cascais and Sesimbra, for which the natural terrain configuration is enough to protect local populations from changes in the sea levels. Nevertheless, it should be considered

[50] Considering a 99th percentile wave energy event over a 25-year TWL return value.

that without continuous artificial nourishment interventions (which should be considered as a local option - and not a generalized one - if the economic or natural value of the beach justifies it), the pocketed beaches are projected to disappear or be extensively reduced towards the end of the 21st century.

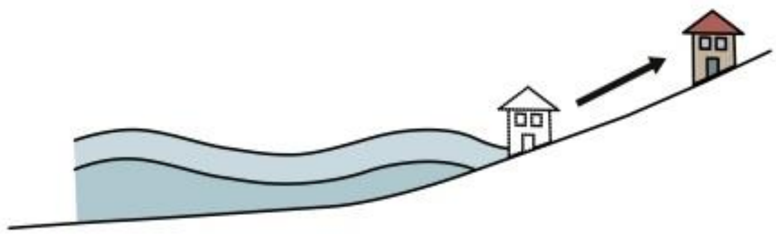
Artificial nourishment
Source: Paula Figueiredo



Accommodation of adherent structures
Source: www.playocean.net

Cliff stabilization

Nature-based solution for dune rehabilitation and preservation



Planned relocation

Figure 2.55 – Examples of adaptation measures to be applied in the Área Metropolitana de Lisboa region, and present in the proposed adaptation pathways of Figure 2.57.

The demographic and cost-benefit analysis performed for the Área Metropolitana de Lisboa region is expressed in Table 2.34. Under the RCP4.5 scenario, more than 18400 habitants (according to the CENSOS2021) are projected to become vulnerable[51] until the end of the 21st century, from over 4500 vulnerable buildings. Total inaction costs related to patrimonial losses (without adaptation measures; TIC) top at over 3341 and 3868 million € by 2070 and 2100, respectively, for all coastlines (both inland and ocean-facing ones). The portion of the TIC associated to each coastal municipality of the Área Metropolitana de Lisboa is depicted in Figure 2.56. Total adaptation costs (TAC), calculated exclusively for ocean-facing coastlines, do not exceed 372 and 596 million €, below the TIC for the same coastlines (1252 and 1387 million €). Therefore, fostering adaptation strategies is recommended for the Área Metropolitana de Lisboa region, with an estimated economic benefit of 880 and 791 million € by 2070 and 2100 under RCP4.5. Bear in mind, however, that while the cost effectiveness of adaptation for the ocean-facing coastlines is expected to be greater for this region in comparison with Norte and Centro, most of the vulnerable areas are located in the Tagus River estuary, for which adaptation might require potentially

[51] *i.e.*, exposed to at least a 100-year return period flooding event.

costly strategies, such as building additional dykes (to postpone relocation efforts and minimize the effects of saltwater intrusion in the agricultural fields of the region), which were not considered in the analysis.

Table 2.34 – Demographic (number of vulnerable residents and buildings projected as vulnerable, *i.e.*, under CVI) and economic cost analysis considering the total inaction costs (TIC) and the total adaptation costs (TAC) in the Área Metropolitana de Lisboa, by 2070 (end of the 2041-2070 period) and 2100 (end of the 2070-2100 period), under the RCP4.5 scenario.

Área Metropolitana de Lisboa (RCP4.5 scenario)	2070	2100
Number of residents under CVI	15856	18489
Number of buildings under CVI	4020	4529
TIC from 2024 onwards – maximum (M€)	3341.2	3868.3
TIC from 2024 onwards – maximum for ocean-facing coastlines (M€)	1252.2	1387.0
TAC from 2024 onwards for ocean-facing coastlines (M€)	372.1	596.4
Annualized maximum TIC (M€/year)	71.1	50.2
Annualized maximum TIC for ocean-facing coastlines (M€)	26.7	18.0
Annualized TAC for ocean-facing coastlines (M€/year)	7.9	7.7

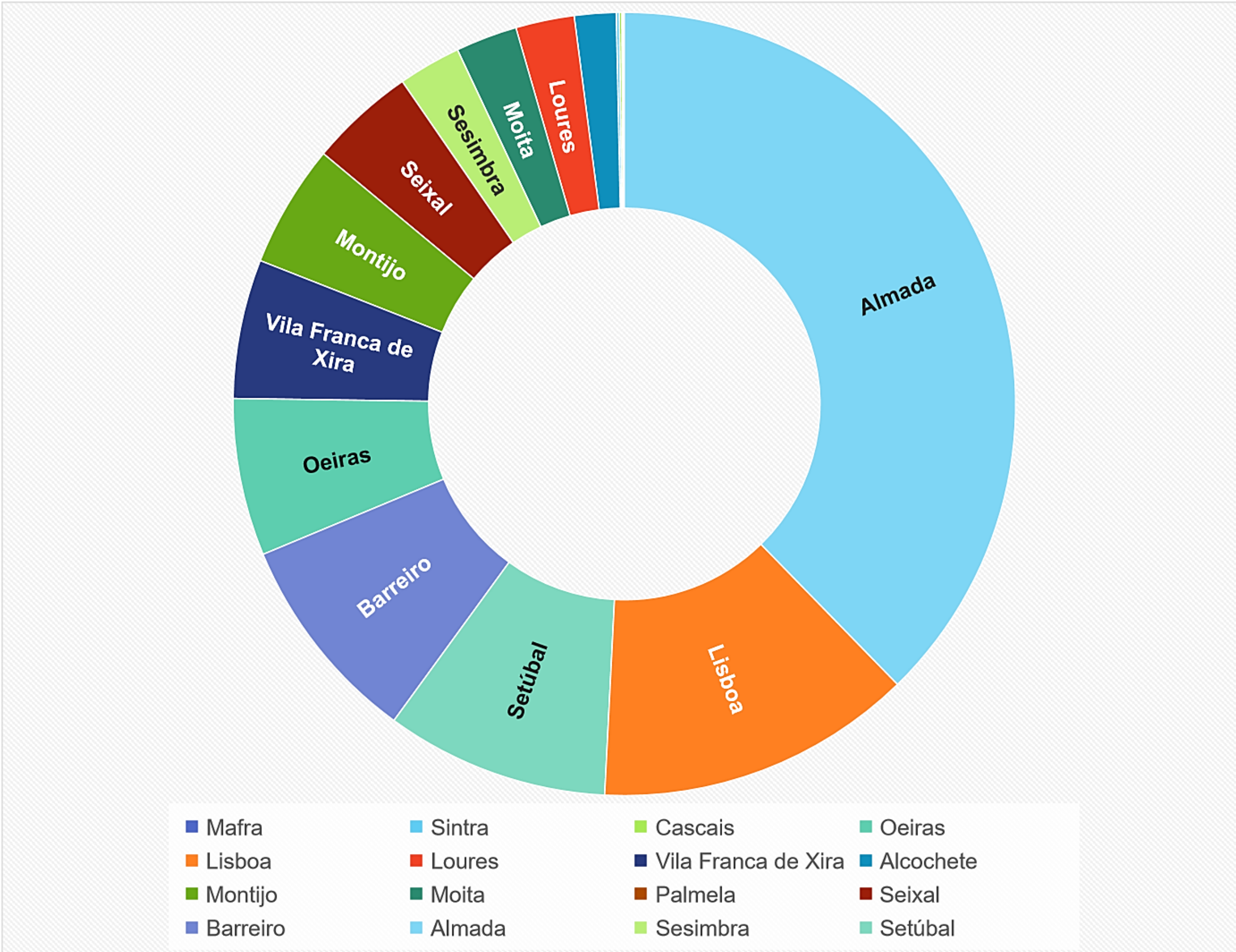


Figure 2.56 – Portion of the TIC (until 2100 under RCP4.5) associated to each coastal municipality of the Área Metropolitana de Lisboa.

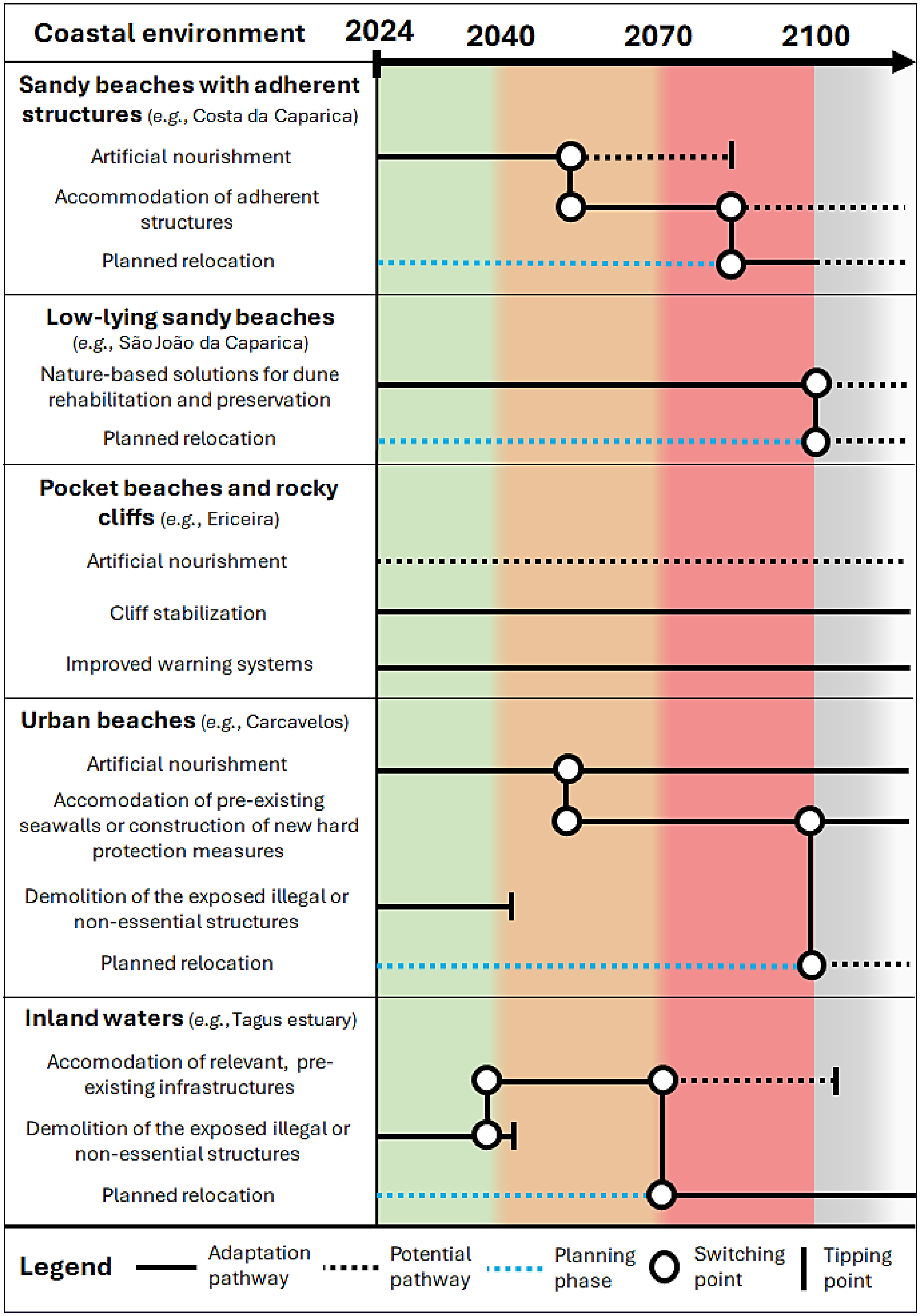


Figure 2.57 – Proposed adaptation pathways along the five identified environments present in the Área Metropolitana de Lisboa NUTSII region, departing from the year 2024, and spanning until the end of the 21st century. The pathways in full correspond to the most viable adaptation strategy for each coastal environment.

2.3.4. Forest fires

The Area Metropolitana de Lisboa (AML), encompassing the Portuguese capital and its surrounding municipalities (Figure 2.58), experiences a Mediterranean climate characterized by hot, dry summers and mild, wet winters. These climatic conditions, coupled with the region's extensive vegetation cover, pose a significant wildfire risk during the summer months. High temperatures and low humidity levels contribute to the rapid spread of wildfires, exacerbated by occasional strong winds. The area's topography, featuring hilly terrain and dense forests, further amplifies the fire danger. Authorities deploy comprehensive wildfire prevention and management strategies, including controlled burns, forest management practices, and public awareness campaigns, to mitigate the risk and safeguard the region's residents and ecosystems. Despite these efforts, vigilance and preparedness remain crucial to address the persistent threat of wildfires in the Area Metropolitana de Lisboa.

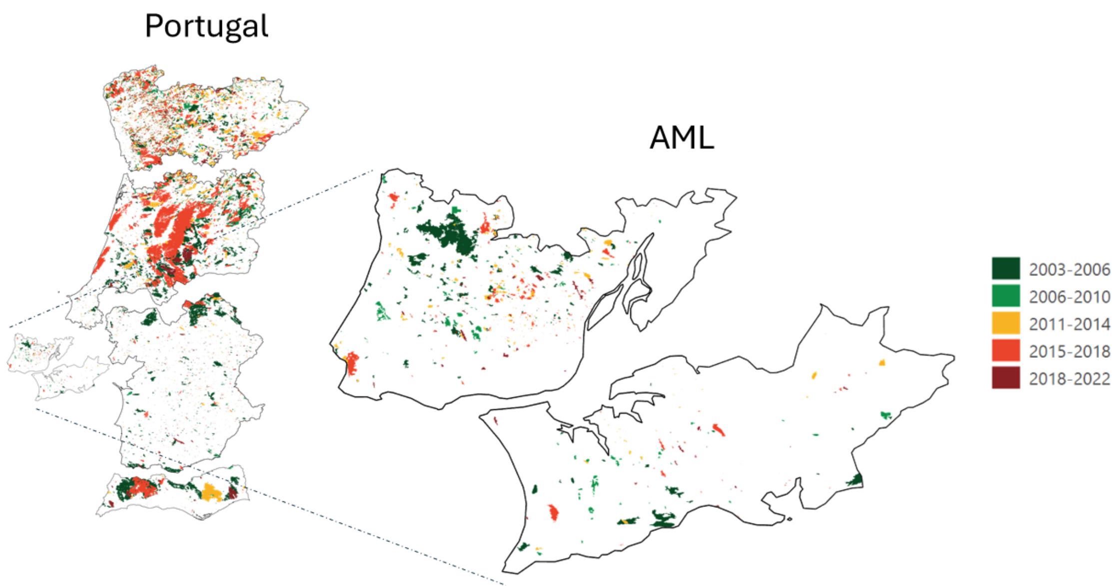


Figure 2.58 – Highlight of AML burned area, with the colours representing the period where the last occurrence took place.

Meteorology is key in defining the composition and structure of vegetation fuels but also holds a central position in determining the susceptibility of these fuels to fire. Human activities and vegetation management practices contribute to the present state of vegetation fuels, while their typology is intricately linked to the broader ecological domains they inhabit. Weather effects exert a profound influence on the vulnerability of vegetation fuels to ignition. They can control the moisture content of different fuels, enabling rapid wetting or drying of fine fuels such as litter, needles, mosses, and twigs. The response is comparatively slower for coarser wooden fuels. The moisture levels in these various fuels, coupled with meteorological factors like wind speed, collectively influence the ease of ignition, potential propagation, and severity of a fire. Recognizing the pivotal importance of meteorology in fire danger assessment is imperative for developing effective strategies for wildfire preparedness and adaptation. A comprehensive understanding of how meteorological conditions interact with other factors contributes significantly to the ability to predict and manage wildfires. Forest management practices, such as prescribed burning, fuel reduction treatments, and landscape-scale planning are essential for reducing fire risk and enhancing ecosystem resilience. Integrating these practices with other fields of expertise, such as ecology, hydrology, and land-use planning, can help optimize adaptation strategies and minimize trade-offs between conservation and fire management objectives. The AML region values its forests for the multitude of ecosystem services they provide, including carbon sequestration, biodiversity conservation, soil stabilization, and water regulation, contributing significantly to the region's environmental health and sustainability.

Meteorological forecasts and early warning systems are critical tools for mitigating fire risks and facilitating timely response efforts. Enhanced monitoring technologies, such as remote sensing, GIS mapping and decision support systems, provide valuable data and insights for fire management decision-making. However, implementing these strategies requires overcoming various challenges, including limited funding, conflicting land-use priorities, regulatory constraints, and social resistance. Addressing these barriers and fostering collaboration between government agencies, non-profit organizations, private landowners, and local communities is essential for effective wildfire management in the AML region.

Hence, the future meteorological danger was assessed by taking advantage of the enhanced Fire Weather Index (FWIe)[52]. It is projected a significant increase in the number of extreme fire danger days (Table 2.35), i.e., the number of days where FWIe is extremely high. For the RCP4.5 more 10 (12) days in extreme fire danger for the mid- (end-) century are projected with respect to the historical values; slighter changes for the RCP2.6 are projected, from additional +4 days, and for the RCP8.5 the number of extreme fire danger can escalate more +25 at the end of the century, more than doubling the 15-days mark observed in the historical climate.

Table 2.35 – Additional number of days per extended summer (June to September) with extreme fire danger for different emission scenarios compared to the present climate.

AML	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Additional days (present climate = 15 days)	+4	+10	+14	+4	+12	+25

[52] The enhanced FWI is a meteorological fire danger index that combines an atmospheric instability parameter.

The 2022 Palmela wildfire affected 415 ha and resulted in estimated losses of 158,000 euros, which corresponds to about 380 euros/ha. This highlights the urgent concern about the potential doubling of days with extreme meteorological danger in the region. In the current climate context, assuming similar losses per ha, the cumulative financial toll of forest fires over the past 20 years stands at around 9 million euros, i.e., about 430,000 euros/year.

From the probabilistic model developed in the context of RNA2100, it is possible to estimate that the likelihood of having forest fires of similar intensity as the 2022 Palmela event can be near 2 times the historical frequency, in agreement with the probability of exceedance of a given fire radiative power under the RCP4.5. Without proactive adaptation measures, the projected losses (Table 2.36) could escalate to nearly 830,000 euros/year under RCP4.5 (almost doubling the 430,000 euros/year mark).

Table 2.36 – Projected losses without implementing adaptation measures, in million euros/year for AML.

Alentejo (No adaptation)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Losses (million euro/year)	0.80	0.83	0.89	0.64	0.83	1.13

In response to the escalating threat of forest fires exacerbated by climate change, it is paramount for the AML region the recognition of the critical importance of implementing adaptation strategies to safeguard its natural landscapes and communities. Drawing upon insights from diverse fields of expertise, including forest management and ecology.

Acknowledging the invaluable role of forest management practices in mitigating fire risk, efforts are underway to implement targeted interventions aimed at reducing fuel loads and enhancing ecosystem resilience. By leveraging knowledge of the region's diverse forest types, which range from cork oak forests to pine stands and Mediterranean scrublands, tailored management strategies can be developed to optimize fire prevention and suppression efforts. This includes prescribed burning, selective thinning and creating strategic firebreaks to interrupt the continuity of fuel and limit fire spread.

Following the objectives of *Roadmap for carbon neutrality 2050 (RNC2050)*, a paramount objective is to significantly decrease the annual burned area to a fraction of its current extent by 2050, marking a substantial reduction. This necessitates meticulous planning for the utilization of post-fire areas, prioritizing reforestation efforts with species resilient to fire and conducive to carbon sequestration, thus preventing deforestation and the conversion of forests into less productive land covers like scrubland. Additionally, adopting effective fire prevention measures, such as utilizing small ruminants to manage combustible materials, is crucial to mitigate fire risks and protect forest ecosystems. Enhancing forest management practices is fundamental to augmenting average productivity and resilience. Measures such as optimizing forest management techniques, intensifying fire prevention measures, and selecting more productive and climate-resilient species will lead to increased forest density and carbon sequestration capacity. By focusing on both production and protection species, the health and sustainability of forest ecosystems can be bolstered. Furthermore, accelerating afforestation efforts and curtailing the expansion of non-forest land uses, particularly urbanized areas, floodplains, and scrublands, are essential. By prioritizing afforestation and sustainable land use practices, the AML region can effectively mitigate climate change impacts, enhance ecosystem services, and foster a resilient and sustainable future for both nature and communities.

However, effective adaptation requires more than just forest management; it necessitates a holistic approach that integrates education and awareness initiatives to foster a culture of fire prevention and safety. By engaging individuals of all ages, from school children to adults, in educational programs and outreach campaigns, communities can become active participants in wildfire prevention efforts. Understanding the ecological importance of forests, the risks posed by irresponsible behaviours such as discarded cigarettes or poorly managed outdoor activities, and the importance of adhering to fire restrictions are essential components of building a resilient society in the face of escalating fire risks. In addition to proactive measures, a responsive approach is crucial for addressing immediate threats during periods of extreme meteorological danger. By leveraging advances in meteorological forecasting and early warning systems, authorities can anticipate and prepare for heightened fire risk on days with adverse weather conditions. This requires collaboration across disciplines, including meteorology, climatology, and data science, to develop robust predictive models that integrate real-time data on weather patterns, fuel moisture content, and vegetation stress indicators. The CEASEFIRE[53] platform is an example of such collaboration, with customised weather information for forest fire prevention, planning and fighting. By harnessing this knowledge and technology, decision-makers can make informed decisions about resource allocation, emergency response, and community evacuation, ultimately minimizing the impact of wildfires on lives, property, and ecosystems. While challenges remain in implementing these adaptation strategies, including technical complexities and resource constraints, the collective efforts of stakeholders from various fields of expertise underscore the urgency and importance of proactive climate adaptation in the AML region.

By integrating insights from forest management, ecology, meteorology and education, communities can build resilience to the growing threat of forest fires and ensure the long-term sustainability of their natural environment and way of life. These insights can be put in place under the three types of strategies that were assessed. One focused only on awareness measures, other on awareness and coercive measures, and the last

[53] https://ceasefire.pt

only on coercive measures. Awareness measures cover initiatives such as continuous education and capacitation of the society. On the other hand, coercive measures encompass actions such as targeted fines. These adaptation measures aim to reduce ignitions and the costs related to large wildfires. For example, Figure 2.59shows the projected losses without adaptation (black bar) and with implementation of adaptation measures (blue, green, and orange bars), in million euros/year for AML. Focusing on RCP4.5, the 430,000 euros/year mean value may reach 830,000 euros/year under climate change, which means an increment of 400,000 euros/year.

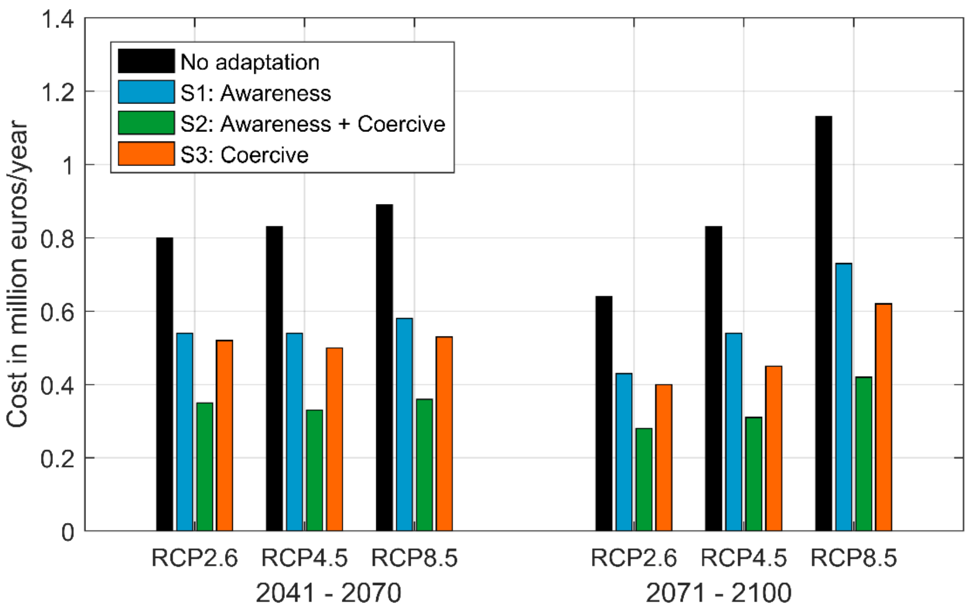


Figure 2.59 – Projected cost of no adaptation (black bar) and cost with implementation of adaptation strategies of Awareness (blue bars), Awareness + Coercive (green bars), and Coercive (orange bars), in million euros/year for AML, under RCP2.6, RCP4.5, and RCP8.5 for the middle of the century (2041 – 2070; left) and the end of the century (2071 – 2100; right).

With a strategy focused on awareness, it is possible to reduce the losses to about 540,000 euros/year. It is however important to note that with the advancement of time, climate change will severely impact the number of days in extreme danger, and consequently coercive strategies to reduce the number of ignitions and consequently burned area may be used. These strategies can represent savings 290,000 euros/year. However, it is essential to note that a pathway focused on both awareness and coercive strategies brings better results, even decreasing the annual cost of the last 20 years to about 330,000 euros/year, representing savings of the order of around half a million euros/year. Figure 2.60 shows the adaptation pathway for AML focused on RCP4.5. Several adaptation and mitigation strategies were already implemented and are expected to continue being implemented in the coming years. Awareness strategies should be first implemented to alert and educate society to the perils of climate change and its impact on forest fires. Eventually, in the most dangerous periods, coercive strategies should be implemented. However, with the increase in global warming, a mix between awareness and coercive continuous strategies must be implemented to prevent tragedies such as the 2022 Palmela fire to become the new normal.

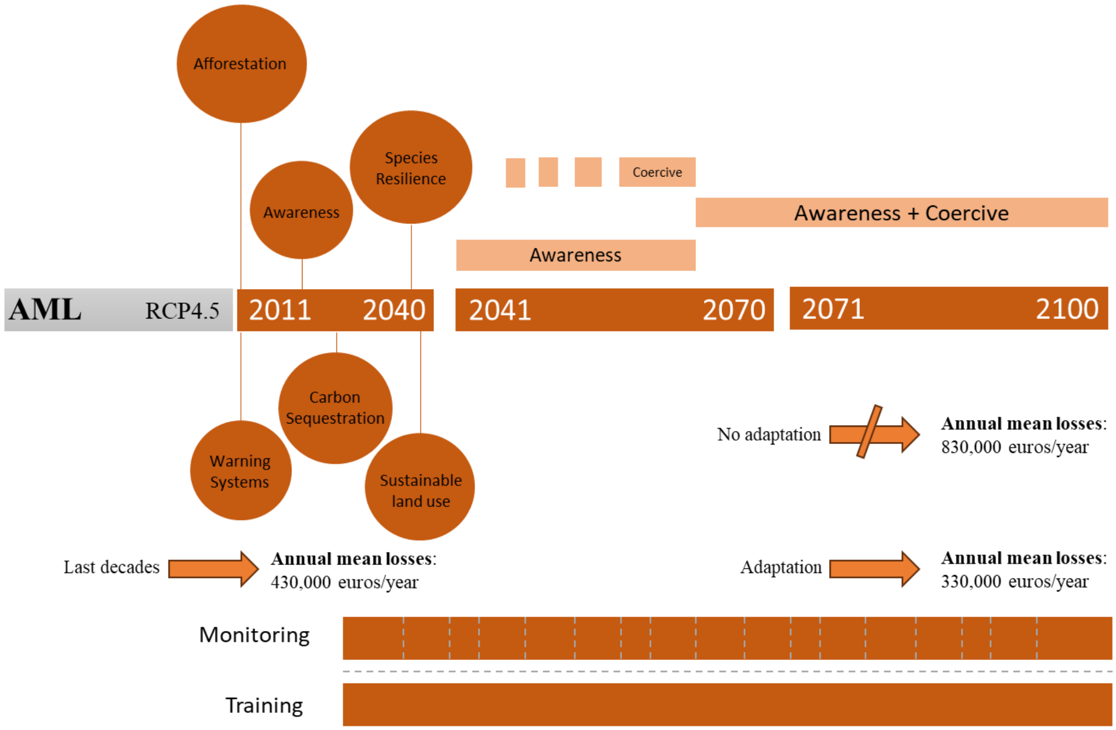


Figure 2.60 – Adaptation narrative for forest fires sector until 2100 for AML under RCP4.5.

2.4. Alentejo

2.4.1. Climate projections

The Alentejo region is projected to experience more significant warming compared to the global mean (Figure 2.61 and Table 2.37). Projections indicate a more pronounced warming in summer than in winter across all climate scenarios. In the RCP4.5 scenario, the Alentejo region is projected to undergo a temperature rise of +1.9 to +2.7 ºC. Even under the RCP2.6 scenario, an increase in annual temperature of 1.4 ºC is expected during the 21st century. Under the RCP8.5 scenario, temperature increases of +4.2 ºC and +4.8 ºC are projected by the end of the 21st century respectively for maximum and minimum temperatures.

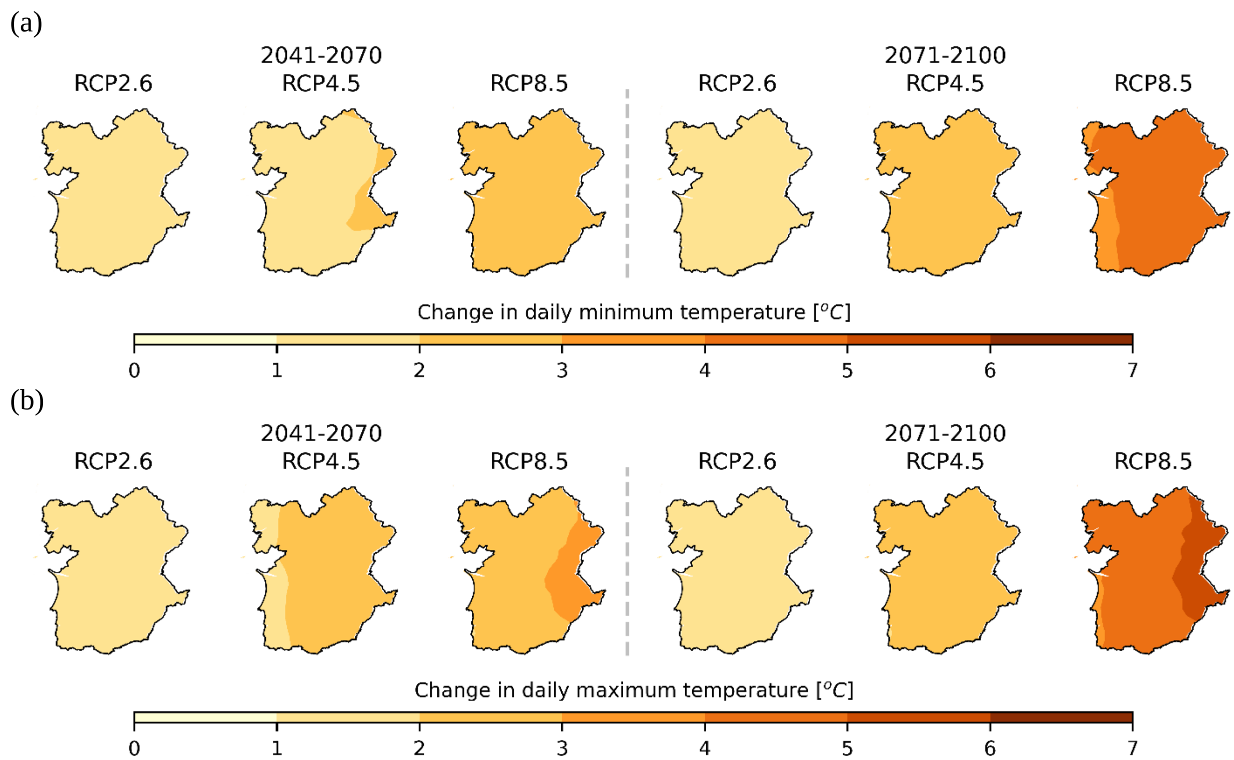


Figure 2.61 – Future projected changes in daily (a) minimum and (b) maximum temperature (ºC) for the Alentejo NUTS II region.

Table 2.37 – Climatological annual mean daily minimum (Tn) and maximum (Tx) temperature (ºC) for the reference period (Historical – 1971-2000); and, future projected changes in daily minimum and maximum temperature (ºC) for the Alentejo NUTS II region.

Alentejo	1971-2000 Historical	Differences	2041-2070			2071-2100		
			RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
T_n (°C)	10.0	ΔT_n (°C)	1.4	1.9	2.5	1.4	2.4	4.2
T_x (°C)	21.4	ΔT_x (°C)	1.5	2.1	2.8	1.4	2.7	4.8

Changes in precipitation are greatly dependent on the season and the future emission scenario. Future projections suggest a decline in mean precipitation across the 21st century, promoting a rise of aridity in Alentejo (Figure 2.62 and Table 2.38). Significantly, the RCP4.5 scenario portrays a distinct decline in annual precipitation, with projected reductions of around -14% by the end of the 21st century. For the RCP2.6 scenario, the precipitation changes are negligible, fluctuating within -0.5% and +1.55%. For the RCP8.5 scenario, the projections point to an annual decrease exceeding -28% by the end of the century. Independently of the emission scenario, the decline of precipitation predominantly occurs in spring, summer and autumn.

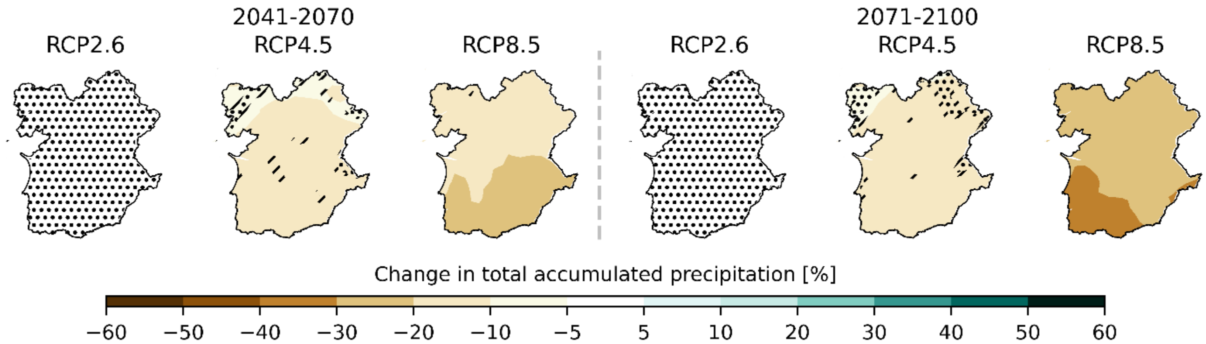


Figure 2.62 – Future projected relative changes in annual accumulated precipitation (%) for the Alentejo NUTS II region. Grid-points where the precipitation does not specify changes statistically significant are identified by dotted hatching.

Table 2.38 – Climatological annual mean accumulated precipitation (Pr) (mm) for the reference period (Historical – 1971-2000); and, future projected relative/absolute changes in annual accumulated precipitation (%/mm) for the Alentejo NUTS II region.

Alentejo	1971-2000 Historical	Differences	2041-2070 RCP2.6	2041-2070 RCP4.5	2041-2070 RCP8.5	2071-2100 RCP2.6	2071-2100 RCP4.5	2071-2100 RCP8.5
$Pr\ (mm)$	656.9	ΔPr (%)	-0.3	-12.4	-18.8	1.5	-14.3	-28.6
		$\Delta Pr\ (mm)$	-2.7	-76.6	-119.1	13.8	-93.0	-182.5

As a result of the warming, the frequency and intensity of extreme temperatures will undergo changes, which are less (more) pronounced under the RCP2.6 (RCP8.5) scenario (Figure 2.63). Concurrent with the rise in maximum temperatures, the occurrence of hot days[54], as well as summer[55] and extremely hot days[56], is projected to escalate. In the historical period (1971-2000), the number of hot days ranges between 40 and 100 days from the littoral to inland. For the RCP4.5, more 35 hot days are expected at the end of the century. For the RCP2.6, the increase is close to 20 days, but for the RCP8.5 the number of hot days is projected to duplicate when compared to the historical period, with more 60 hot days annually. Furthermore,

[54] Hot days: number of days where maximum temperature exceeds 30ºC.
[55] Summer days: number of days where maximum temperature exceeds 25ºC.
[56] Very hot days: number of days where maximum temperature exceeds 35ºC.

heatwaves[57] are projected to become more frequent, intense, and longer lasting. In the historical period occurs approximately 1 to 2 heatwaves per year with a mean duration around 6 days per event. Under the RCP4.5, it is expected an increase in the number of heatwaves between 3 and 5 throughout the 21st century. Under the RCP2.6, the occurrence of more 2 heatwaves per year is projected. However, considering the RCP8.5, the projections point to more 9 heatwaves per year. Aligned with the increase in the number of heatwaves, the mean duration of these events is also projected to increase. For the RCP4.5, the mean duration of heatwaves is projected to increase around 2 days. A similar result is expected for the RCP2.6, whilst under the RCP8.5, the expected increase is between 3 and 5 more days in heatwave, when compared with the historical period. Aligned with the rising of minimum temperature, tropical nights[58] are expected to become more prevalent, while the incidence of cold days[59] will diminish. In fact, the annual tropical nights projections point to more around 20 under the RC4.5 and more 10 under the RCP2.6; and, additionally around 60 tropical nights per year according the RCP8.5 scenario.

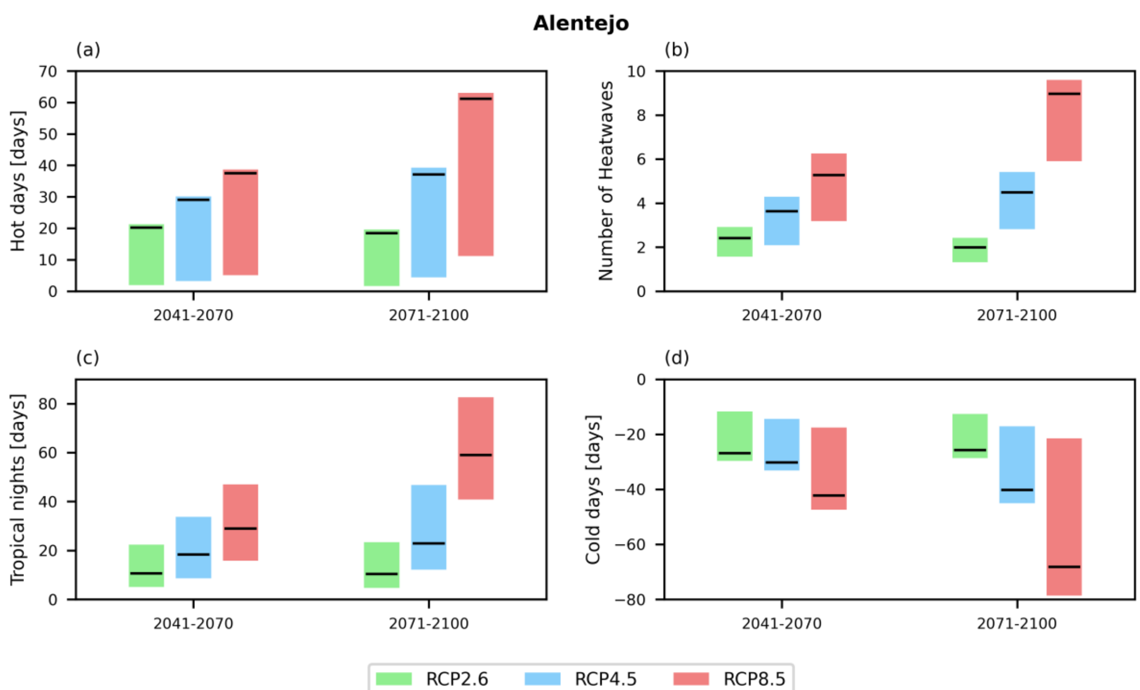


Figure 2.63 – Distribution of the projected changes in (a) hot days [days/year], (b) number of heatwaves per year, (c) tropical nights [days/year] and (d) cold days [days/year] for all gridpoints in Alentejo's region. The straight black line represents the mean value for the Alentejo's region. Individual boxes span from the spatial minimum to the maximum value of the Alentejo's region.

[57] Heatwave is defined as a period of five or more consecutive days with maximum temperature above the 90th percentile.
[58] Tropical nights: number of days where minimum temperature exceeds 20ºC.
[59] Cold days: number of days where minimum temperature is below 7ºC.

In line with the decline in mean accumulated precipitation, a reduction in the number of wet days[60] and, consequently, an increase in the number of dry days, is projected across the 21st century (Figure 2.64). For the RCP4.5 scenario, less 10 wet days is projected throughout the 21st century. For the RCP2.6 scenario, however, negligible changes throughout the century are projected, with a slight decrease during the mid- and end-21st century around 4 wet days. For the RCP8.5 scenario, the projections point to less 27 wet days by the end of the 21st century. The number of consecutive dry days[61] is expected to increase, enhancing drying conditions. Regarding the number of days with moderate[62] and heavy[63] precipitation, clear projected reductions are evident, especially under the RCP4.5 and RCP8.5 scenarios. The maximum 5-day accumulated precipitation[64] is projected to slightly increase, in a rather heterogeneous across the territory and with larger values over the northern area of Alentejo's region. Under the RCP4.5 scenario, the increases can reach more 20 mm on average (in the historical period the MaxPr5d value is around 200 mm). The results for the RCP2.6 scenario are similar to the ones for the RCP4.5 in the mid-century but for the end of the century no change is projected on average. For the RCP8.5 scenario, the increase of maximum 5-day accumulated precipitation can reach more 60 mm. In spite of the projected decrease of the number of wet days, projections suggest a concentration of rainfall into shorter time frames, implying an intensification of moderate/heavy precipitation regardless of the scenario.

[60] Wet days: number of days with precipitation exceeding 1 mm/day.
[61] Dry days: number of maximum consecutive dry days where precipitation is below 1 mm/day.
[62] Moderate precipitation days: number of days with precipitation exceeding 10 mm/day.
[63] Heavy precipitation days: number of days with precipitation exceeding 20 mm/day.
[64] Maximum of 5-day accumulated precipitation.

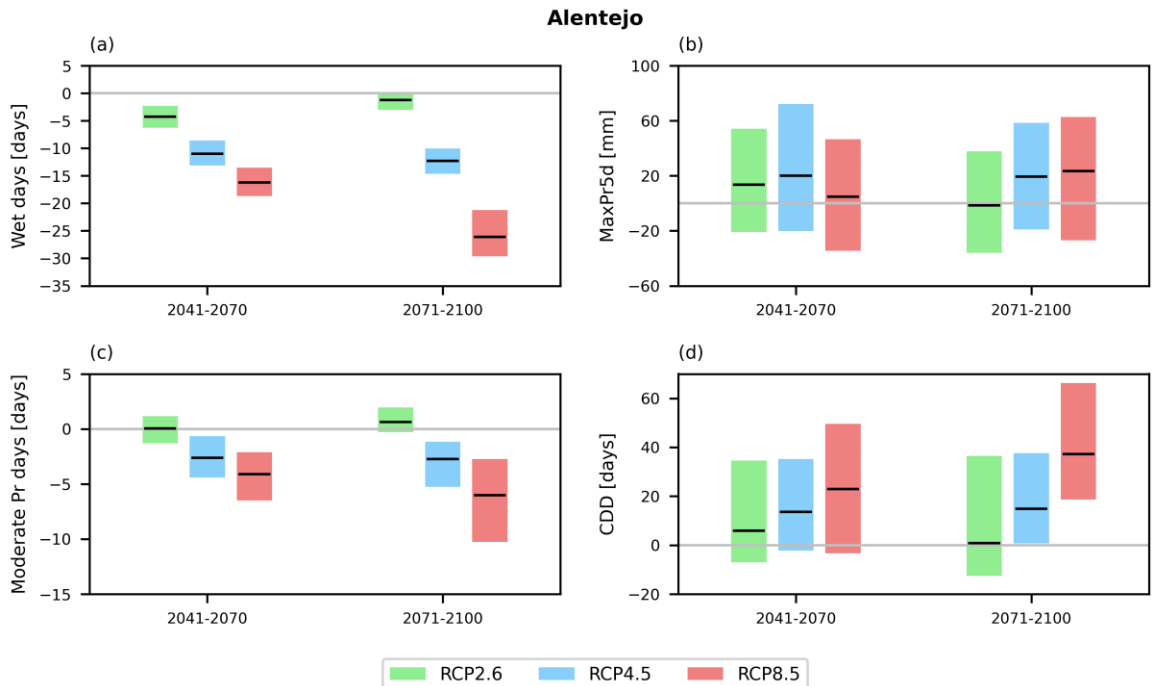


Figure 2.64 – Distribution of the projected changes in (a) wet days [days/year], (b) maximum of 5-day accumulated precipitation (MaxPr5d) [mm], (c) moderate precipitation days [days/year] and (d) consecutive dry days (CDD) [days] for all gridpoints in Alentejo's region. The straight black line represents the mean value for the Alentejo's region. Individual boxes span from the spatial minimum to the maximum value of the Alentejo's region.

A summary of confidence in the direction of projected changes in climate means and indices is presented in Table 2.39. The results give us confidence in climate projections presented here.

Table 2.39 – Summary of confidence in the direction of projected change in climate means and indices for the Alentejo NUTS II region. Temperature: climatological annual mean daily minimum (Tn) and maximum (Tx) temperature, hot days (Txg30), number of heatwaves per year (HWN), tropical nights (Tng20) and cold days (Tnl7); Precipitation: climatological annual mean accumulated precipitation (Pr), wet days (Prg1), maximum of 5-day accumulated precipitation (MaxPr5d), moderate precipitation days (Prg10) and consecutive dry days (CDD). A standard deviation of 0.25, 1, 2, 3 corresponds to a moderate, strong, very strong, severe increase/decrease of the variables. Values shown are ensemble median changes. Colours illustrate the model's agreement within the multi-model ensemble.

Alentejo							
		2041-2070			2071-2100		
		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Temperature	Tx	↑↑	↑↑↑	↑↑↑	↑↑	↑↑↑	↑↑↑
	Txg30	↑	↑↑	↑↑↑	↑	↑↑	↑↑↑
	HWN	↑	↑↑	↑↑↑	↑	↑↑	↑↑↑
	Tn	↑↑	↑↑↑	↑↑↑	↑↑	↑↑↑	↑↑↑
	Tnl7	↓↓	↓↓	↓↓↓	↓	↓↓↓	↓↓↓
	Tng20	↑	↑↑↑	↑↑↑	↑	↑↑↑	↑↑↑
Precipitation	Pr	⊠	↘	↘	⊠	↘	↓
	MaxPr5d	↗	↗	⊠	⊠	↗	↗
	Prg1	↘	↘	↓	⊠	↘	↓
	Prg10	⊠	↘	↘	⊠	↘	↘
	CDD	↗	↗	↑	⊠	↗	↑

↑↑↑	Change above 3 standard deviations
↑↑	Change above 2 standard deviations
↑	Change above 1 standard deviation
↗	Change above 0.25 standard deviations
⊠	Change between -0.25 and 0.25 standard deviations
↘	Change below -0.25 standard deviations
↓	Change below -1 standard deviation
↓↓	Change below -2 standard deviations
↓↓↓	Change below -3 standard deviations

	High agreement: at least 80% of models show a positive change
	Low agreement: at least 50% of models show a positive change
	No agreement: models disagree on the direction of change
	Low agreement: at least 50% of models show a negative change
	High agreement: at least 80% of models show a negative change

2.4.2. Water scarcity and stress on crops

NUTS II Alentejo includes, within its administrative boundaries, four River Basins, among which RH5 – Tejo and Ribeiras do Oeste, RH6 – Sado, and RH7 – Guadiana stand out (Figure 2.65). It contains the country's two largest hydro-agricultural developments. The primary one is associated to the Multipurpose Project of Alqueva (EFMA), featuring reservoirs like Alqueva and Pedrógão within RH7, alongside others like Alvito, Vale do Gaio, or Roxo, situated in RH6. The second significant hydro-agricultural development is the Vale do Sorraia, which comprises several reservoirs, with Montargil and Maranhão being the main ones, situated in RH5. It is also worth mentioning the Santa Clara reservoir, which supplies water to the hydro-agricultural development of Mira, due to its relevance in the cultivation of small fruits, as well as floriculture and ornamental plants. Another significant development is the hydro-agricultural exploitation of Vale do Sado, relying on the Pêgo do Altar and Vale do Gaio reservoirs, primarily for rice cultivation, all falling under RH6.

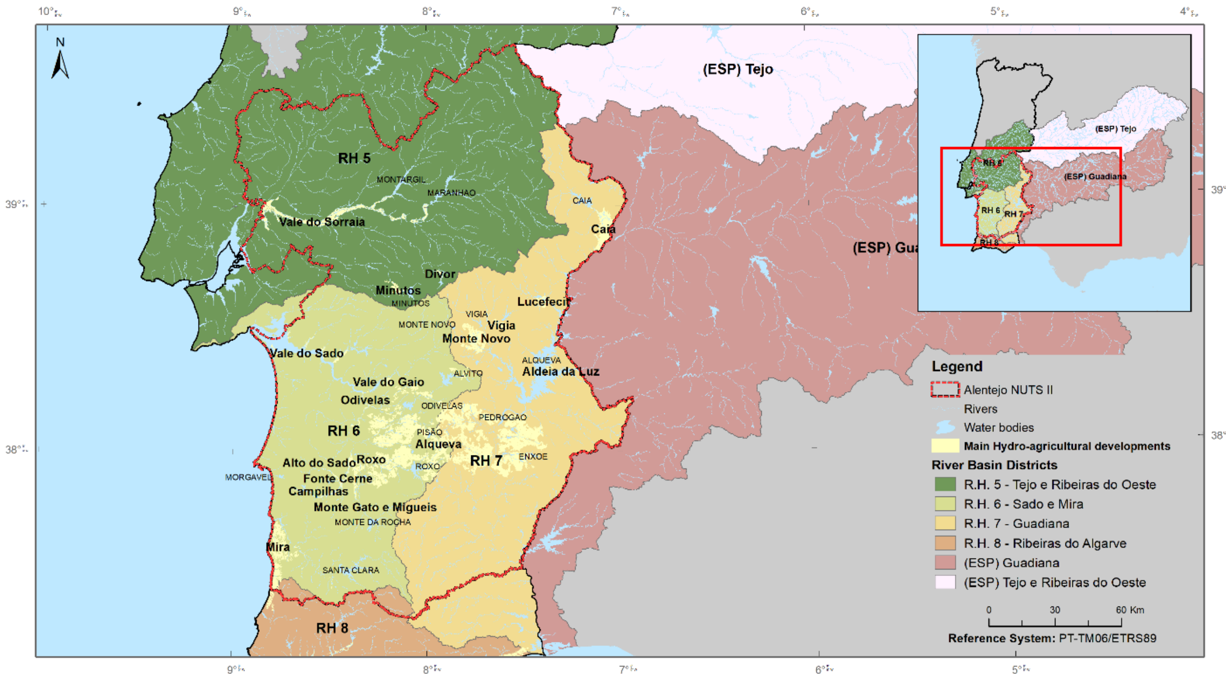


Figure 2.65 – NUTSII Alentejo and River Basins location: RH5 – Tejo e Ribeiras do Oeste, RH6 Sado, RH7 Guadiana and RH8 Ribeiras do Algarve.

In 2022, the Alentejo region was the leading national producer of olives and dry legumes, contributing with 50.1% and 30.7%, respectively, to the country's total production. However, the most significant crop for regional productivity is processing tomatoes, accounting for a 31.3% contribution and primarily cultivated in the Lezíria do Tejo sub-region. Olive production is widespread throughout the NUTS II Alentejo region with particular relevance in the hydro-agricultural development associated with the Multipurpose Project of Alqueva, ranking as the second most productive crop at around 20%. This is closely followed by forage crops, which represent 19.7% of the total production in NUTS II Alentejo.

Considering the full area of the principal River Basins that cross NUTS II Alentejo, climate change scenario projections indicate a decrease in water yield for the RCP4.5 scenario. This trend becomes more pronounced for scenarios with higher concentrations of greenhouse gases in the atmosphere (RCP8.5). However, an increase in water yield is projected from the mid-century onward if concentration levels follow those outlined in the Paris Agreement throughout the 21st century (RCP2.6) (Figure 2.66). Nevertheless, it is essential to emphasize that this does not necessarily imply a reduction in water stress levels within the region. The dynamics of water stress depend on balancing water availability with demands. The Water

Exploitation Index plus (WEI+) is a ratio comparing water use to renewable water resources and serves as a common tool in the European Union and Portugal for assessing this equilibrium.

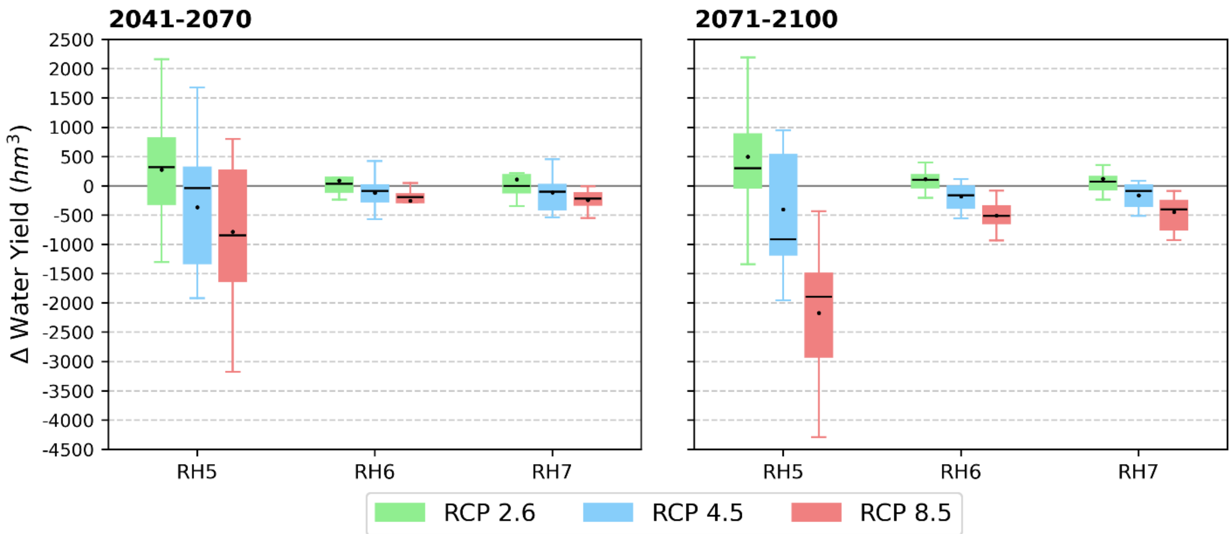


Figure 2.66 – Projected changes in averaged water yield (hm^3) for River Basins RH5 Tejo e Ribeiras do Oeste, RH6 Sado and RH7 Guadiana. Two future periods are shown: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5 and RCP8.5. The black line represents the ensemble median.

While the decrease in water yield may appear relatively small in the RCP4.5 scenarios for RH6 and RH7 the impacts will be quite severe due to the increased water needs of crops due to changes in plant phenology. This becomes evident in the analysis of anomalies in the Water Exploitation Index + (WEI+) for the River Basins that partially overlap with the NUTS II Alentejo region (Figure 2.67), showing in general terms a worsening trend in this index for all three scenarios and the different periods analysed. Even when an increase in water yield is projected, as mentioned for the RCP2.6 scenario, the demand for water tends to rise due to modifications in the water needs of crops, primarily attributed to a slight temperature increase projected for this scenario. The exception to these trends is the River Basin of Tejo e Ribeiras do Oeste, although impacts on the WEI+ are projected, they will be of lesser magnitude, with the increase in RCP4.5 not exceeding +2 percentage points and approaching an additional 12 percentage points in RCP8.5. If concentration levels follow the guidelines set in the Paris Agreement, impacts in the mid-century onward are virtually non-existent.

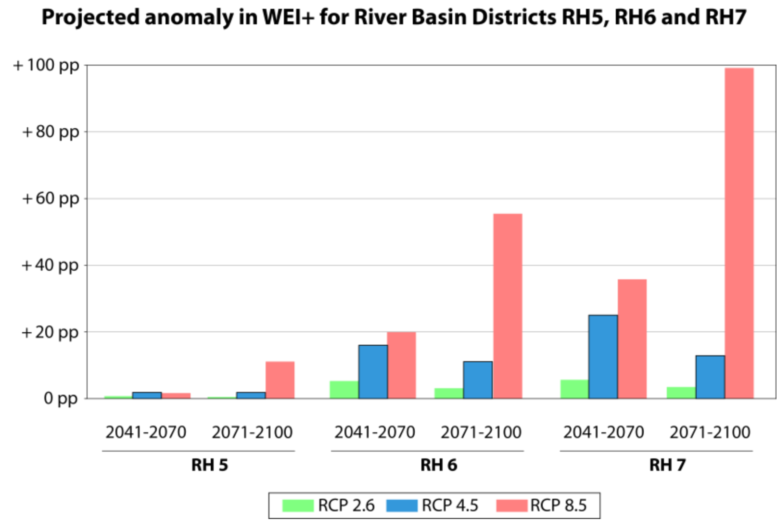


Figure 2.67 – Projected change in WEI+ (in percentage points) for River Basins RH5 Tejo e Ribeiras do Oeste, RH6 Sado, and RH7 Guadiana. Two future periods are shown: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5 and RCP8.5. The presented values refer to the ensemble median.

Climate change can affect both irrigation requirements and productivity of the main crops grown in mainland Portugal. Table 2.40 illustrates these impacts on four crops: tomato, olive grove, corn, and almond, representing 31.1%, 20.4%, 10.5% and 0.8% of the crop's productivity considered in NUTS II Alentejo. For olive groves and almond, relative stability is observed across various climate change scenarios. However, a trend of decreasing productivity is noted for tomato, and grain corn, which could lead to a production decrease of up to -20% for grain corn in RCP4.5, compared to current productivity levels.

Considering all costs and benefits due to climate change in crops, the overall economic losses can amount to more than 121 million euros per year for the time frame 2041-2070 and more than 131 million euros for the period 2071-2100 in RCP4.5. Economic losses in productivity are related to modifications in climatic conditions for the crops currently developed in the region due to changes in plant phenology.

Table 2.40 – Projected changes in productivity in average % for tomato, olive grove, corn, and almond in NUT II Alentejo for two future periods: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5 and RCP8.5. The presented values refer to the ensemble median.

NUTS II Alentejo	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Tomato	-7.6%	-12.6%	-17.6%	-8.9%	-16.0%	-23.0%
Olive grove	-0.3%	-0.5%	-0.7%	-0.1%	-0.5%	-1.3%
Corn	-11.3%	-14.8%	-19.1%	-8.2%	-20.7%	-28.7%
Almond	0.0%	-0.6%	-0.9%	-0.1%	-0.6%	-1.7%

Apart from the need for a careful assessment for the construction of new reservoirs, with updated meteorological and hydrological information, considering compliance with the DNSH (Do No Significant Harm) principle and also, proof that it continues to be an option in climate change scenarios (climate-proof), ensuring resilience now and in the future, it is imperative, firstly, to make a strong commitment to efficiency measures. Action should therefore consider minimizing losses to insignificant levels, reducing natural water consumption, which can be replaced in part by alternative sources such as water for reuse, changing crops to crops more adapted to existing conditions, among others. Therefore, the exercise presented focuses on identifying measures that allow the effects of the increase in the scarcity index, which currently exists, to be nullified throughout the 21st century and for different climate scenarios, through solutions that essentially affect the demand side.

To adapt the Alentejo region to the projected impacts of climate change on water and agroforestry resources, it is proposed that initial measures be implemented as no-regrets actions. These measures notably include promoting the reduction of losses in the distribution network in hydro-agricultural projects and increasing irrigation efficiency throughout the region. Currently, there is significant variation in the reality of hydro-agricultural developments in the region. For example, the hydro-agricultural development of Divor, located in RH5, reports losses in the distribution network of around 40%, while the hydro-agricultural developments of Alqueva report losses of 5%. This measure proposes that all irrigation perimeters achieve distribution network efficiency levels around 90%.

Regarding irrigation efficiency, much has been done in recent years, namely in olive groves, although there is still room for improvement. it is assessed that all irrigation in applicable crops transition to using drip irrigation systems, where irrigation efficiency typically ranges between 90-95%. In Alentejo, the use of this type of irrigation in forage crops, especially in corn, would be particularly relevant.

Subsequently, the simulations include changing current irrigated crops to those with lower irrigation needs (low regrets), combined with other win-win measures such as techniques promoting greater water retention in the soil (e.g., direct seeding, mulching) and the implementation of water retention landscapes (e.g., creating ponds, planting in valleys and berms). This can contribute to a longer maintenance of the balance between water supply and demand in NUTS II through transformative adaptation.

The use of water for reuse (a no-regrets measure) is also a viable solution, although its implementation is highly localized due to the geographical layout of the territory and is primarily directed towards urban or agricultural areas near urban clusters. Additionally, it is advisable to consider reducing water losses in the distribution network for urban purposes, as the overall average of losses is currently reported around 32%, considering the entire NUTS II region.

When all the previous measures fail to maintain the balance between water supply and demand, the creation of desalination plants for agricultural irrigation to address water scarcity (low regrets) should also be considered. This measure is more targeted towards hydrographic regions close to the coast and where significant aggravations of water yield and WEI+ are projected, as is the case in Hydrographic Region RH6.

It is also crucial to ensure the success of the suggested adaptation actions by raising awareness and providing training to farmers. Farmer training should cover adaptive agricultural practices to help them cope with changing conditions, including the implementation of water management techniques, the introduction of drought-resistant crops, and the adjustment of planting and harvesting schedules. In this context, it is worth noting that the impacts of climate change will affect not only water availability but also agricultural productivity. Even if all plant water and nutrient needs are met, productivity losses will occur in scenarios with higher greenhouse gas emissions/concentrations over the century due to changes in plant phenology.

Adaptation in RH6 Sado[65]

In economic terms, the projected impacts of climate change on water availability for RH6 could result in losses averaging up to 565 thousand euros per year in RCP4.5 for the time frame 2041-2070 and 1045 thousand euros for the period 2071-2100. Considering other scenarios, gains can vary on average up to 665 thousand euros (RCP2.6 period 2071-2100), while losses can be as high as 3,3 million euros on average per year (RCP8.5 period 2071-2100).

In this River Basin, a decrease in the average annual volume stored in the reservoirs is projected, with values between -1.4% and 3.7% in the RCP4.5 scenario (Table 2.41). This situation is more severe in the RCP8.5 scenario, where the decrease could reach -27.2% by the end of the century. For the RCP2.6 scenario, it is projected a slight decrease in average stored volumes in reservoirs.

Table 2.41 – Projected changes in average annual volume stored in reservoirs in % for RH6, considering two future periods (anomaly) 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. The presented values refer to the ensemble median.

River Basins (RH6)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Reservoirs Availability	-1.1%	-3.7%	-9.7%	-1.9%	-1.4%	-27.2%

[65] For the adaptation in RH5, please refer to the Adaptation storyline for NUTS II Centro.

With the implementation of the above-mentioned adaptation measures for RH6, the identified economic impacts could be minimized in these River Basins, and some benefits would be achieved. Table 2.42 shows the overall results for RH6 with the percentual changes to the Water Exploitation Index Plus (WEI+) with the implementation of each of the following adaptation measures: reducing system water loss and leakages, improving irrigation efficiency, selection of crops better suited to climate change projections, and wastewater recycling and reuse.

Table 2.42 – Projected change in WEI+ (in percentage points) for RH6 are shown considering two future periods: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. The presented anomalies refer to the ensemble median and consider the following factors: no adaptation, the improvement of irrigation efficiency, the selection of crops better suited to climate change projections, and wastewater recycling and reuse.

River Basins (RH6)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Climate change impacts (no adaptation)	+5.22 pp	+15.95 pp	+19.86 pp	+3.60 pp	+11.16 pp	+55.35 pp
Reducing system water loss and leakages	+1.87 pp	+5.75 pp	+15.50 pp	+0.72 pp	+7.58 pp	+47.77 pp
Improving irrigation efficiency (entails reducing system water loss and leakages simultaneously)	+0.03 pp	+3.74 pp	+8.29 pp	-0.96 pp	+4.43 pp	+43.59 pp
Changing current irrigated crops (entails reducing system water loss and leakages simultaneously)	+0.55 pp	+4.05 pp	+10.85 pp	-0.46 pp	+6.09 pp	+45.25 pp
Wastewater for reuse (entails reducing system water loss and leakages simultaneously)	+1.04 pp	+4.66 pp	+13.08 pp	+0.04 pp	+6.73 pp	+46.11 pp

All of the individually modelled measures bring some benefit to the region through a reduction in the anomalies projected for WEI+. The measure that brings the most benefits to the region, among the ones that were modelled, involves improving irrigation efficiency in combination with reducing system water loss and leakages on hydro-agricultural developments. In this case the anomaly in WEI+ can be reduced by up to 12 percentage points at the end of the century.

Since not all discusses measures were modelled, the prioritisation of all adaptation measures for RH6 is presented in Figure 2.68. The figure outlines the timeline for the full implementation of each measure aimed at mitigating the projected impacts of climate change.

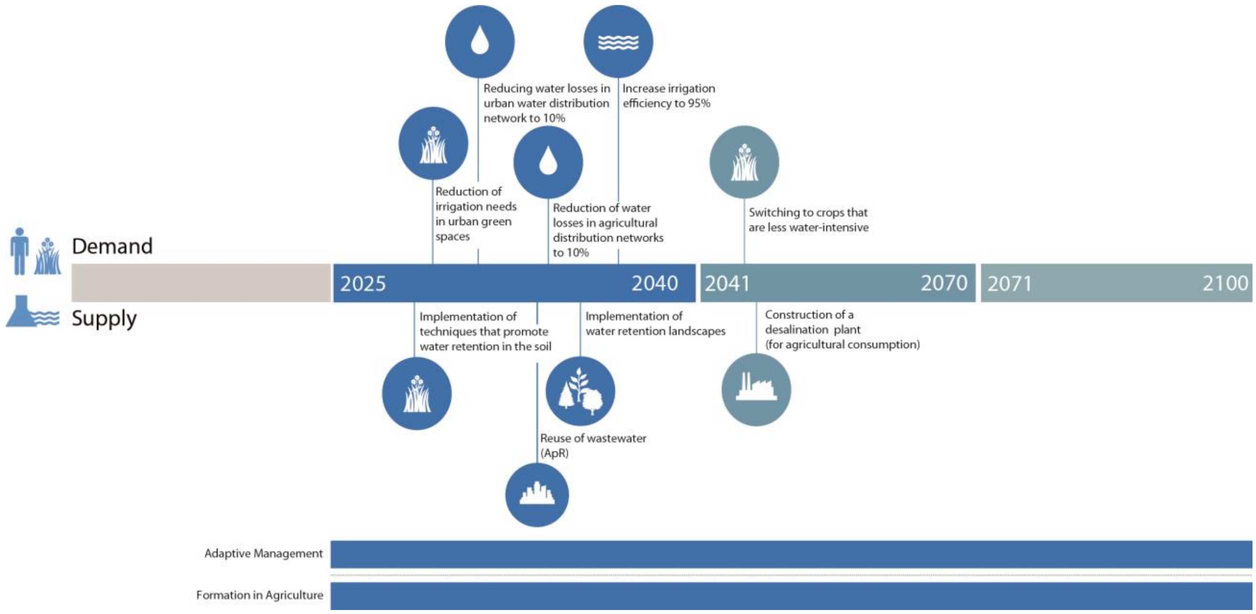


Figure 2.68 – Adaptation narrative for the water resources and agroforestry sectors in RH6 until 2100.

Adaptation in RH7 Guadiana[66]

In economic terms, the projected impacts of climate change on water availability for RH7 could result in losses averaging up to 348 thousand euros per year in RCP4.5 for the time frame 2041-2070 and 317 thousand euros for the period 2071-2100. Considering other scenarios, gains can vary on average up to 263 thousand euros (RCP2.6 period 2041-2070), while losses can be as high as 1,4 million euros on average per year (RCP8.5 period 2071-2100).

In this River Basin, a decrease in the average annual volume stored in the reservoirs is projected, with values between -3.6% and -7.8% in the RCP4.5 scenario (Table 2.43). This situation is even more severe in the RCP8.5 scenario, where the decrease could reach -34% by the end of the century. For the RCP2.6 scenario, no significant changes are expected.

Table 2.43 – Projected changes in average annual volume stored in reservoirs in % for RH7, considering two future periods (anomaly) 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. The presented values refer to the ensemble median.

River Basins (RH7)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Reservoirs Availability	-0.8%	-7.8%	-7.4%	+1.7%	-3.6%	-34.1%

[66] For the adaptation in RH5, please refer to the Adaptation storyline for NUTS II Centro.

With the implementation of the above-mentioned adaptation measures for RH7, the identified economic impacts could be minimized in these River Basins, and some benefits would be achieved. Table 2.44 shows the overall results for RH7 with the percentual changes to the Water Exploitation Index Plus (WEI+) with the implementation of each of the following adaptation measures: reducing system water loss and leakages, improving irrigation efficiency, selection of crops better suited to climate change projections, and wastewater recycling and reuse.

Table 2.44 – Projected change in WEI+ (in percentage points) for RH7 are shown considering two future periods: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. The presented values refer to the multi-model ensemble median and consider the following factors: no adaptation, the improvement of irrigation efficiency, the selection of crops better suited to climate change projections, and wastewater recycling and reuse.

River Basins (RH7)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Climate change impacts (no adaptation)	+5.65 pp	+24.97 pp	+35.69 pp	+3.04 pp	+12.82 pp	+99.03 pp
Reducing system water loss and leakages	+3.48 pp	+11.68 pp	+31.67 pp	+1.20 pp	+7.31 pp	+90.77 pp
Improving irrigation efficiency (entails reducing system water loss and leakages simultaneously)	+2.78 pp	+9.36 pp	+30.40 pp	+0.99 pp	+6.91 pp	+89.53 pp
Changing current irrigated crops (entails reducing system water loss and leakages simultaneously)	+1.93 pp	+5.79 pp	+24.93 pp	+0.59 pp	+6.29 pp	+86.65 pp
Wastewater for reuse (entails reducing system water loss and leakages simultaneously)	+0.69 pp	+4.22 pp	+18.07 pp	-0.78 pp	+5.49 pp	+82.54 pp

All of the individually modelled measures bring some benefit to the region through a reduction in the anomalies projected for WEI+. The measure that brings the most benefits to the region, among the ones that were modelled, involves wastewater recycling and reuse in combination with reducing system water loss and leakages on hydro-agricultural developments. In this case the anomaly in WEI+ can be reduced by up to 17 percentage points at the end of the century.

Since not all discusses measures were modelled, the prioritisation of all adaptation measures for RH7 is presented in Figure 2.69. The figure outlines the timeline for the full implementation of each measure aimed at mitigating the projected impacts of climate change.

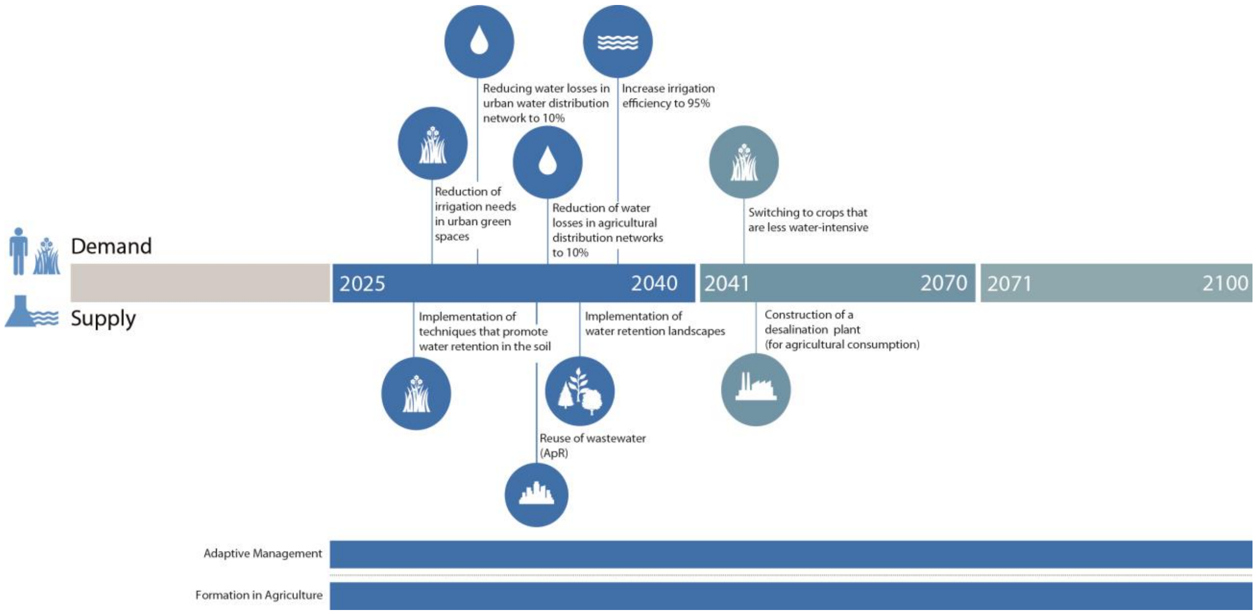


Figure 2.69 – Adaptation narrative for the water resources and agroforestry sectors in RH7 until 2100.

2.4.3. Coastal flooding

The coastal areas of the Alentejo region comprehend a generally low-anthropized system, extending for over 130 km (Figure 2.70). While the northern half of the Alentejo coastline is generally characterized by long sandy beaches (from Troia to Sines; *e.g.*, Praia da Costa da Galé, Praia da Torre, Praia da Comporta, Praia da Fonte do Cortiço), the southern half is dominated by rocky cliffs and pocketed beaches (from Sines to Odeceixe; *e.g.*, Porto Covo, Praia do Malhão, Praia de Almograve, Praia do Tonel, Praia do Carvalhal, Praia da Amália), with generally low sediment stocks. The Sado River estuary extends through the low-lying inland areas between Setúbal and Alcácer do Sal. Other smaller-scale interesting features include the Melides and Santo André coastal lagoons. A few urban beaches are also present, such as the case of Praia Vasco da Gama, in Sines. Although diverse in its coastal environments, this region is shown to be particularly vulnerable to the impacts of rising sea levels and changes in wave climate patterns (the reader is referred to the WP4.5/6 dynamic modelling report).

Figure 2.70 – The Alentejo NUTSII region, depicting the most relevant locations in terms of projected coastal vulnerability.

The vulnerability assessment conducted for the Alentejo region revealed, similarly to the Área Metropolitana de Lisboa, that the coastlines facing inland waters are the ones projected to become more threatened by the increase in the total water levels[67], in comparison to the ocean-facing ones, mostly due to the large extension of low-lying areas surrounding the Sado River estuary (Figure 2.72). Note that although some of the ocean-facing coastlines of the Troia-Sines coastal stretch are locally projected to be highly vulnerable (associated episodic flooding with return periods as frequent as every 4 years; Figure 2.71), the large sedimentary stocks along this coastal environment ensure its increased resiliency to changes in water

[67] The total water level (TWL) is given by the sum of the sea level rise (SLR), tide and storm surge components. For the ocean-facing coastlines, the run-up associated with a 99th percentile energy wave event is also considered.

levels, and therefore, the total area expected to become highly vulnerable in the future is almost one order of magnitude less than for the inland waters, even by the mid-21st century, and under a moderate concentrations' scenario (RCP4.5). Along the outer limits of the Sado River estuary, especially closer to the Sado River mouth, while low-to-moderate vulnerability is projected between 2041 and 2070, high vulnerability can be expected between 2071 and 2100, exposing communities and valuable infrastructure to frequent (or even permanent) flooding.

Considering the Alentejo region as a whole, and for the three classes of vulnerability adopted (low, medium and high, associated to the 100-, 25- and 4-year total water level return values) projections revealed 7.9-9.8 km² of vulnerable ocean-facing coastlines (beaches), and 198.8-212.9 km² of vulnerable coastlines facing inland waters (mostly in the Sado River estuary and coastal lagoon systems; Table 2.45), depending on the future period and scenario. Departing from the intermediate RCP4.5 scenario, on a trajectory closer to the RCP8.5, an increase up to 5.7 km² in the vulnerable areas of Alentejo is projected by 2100.

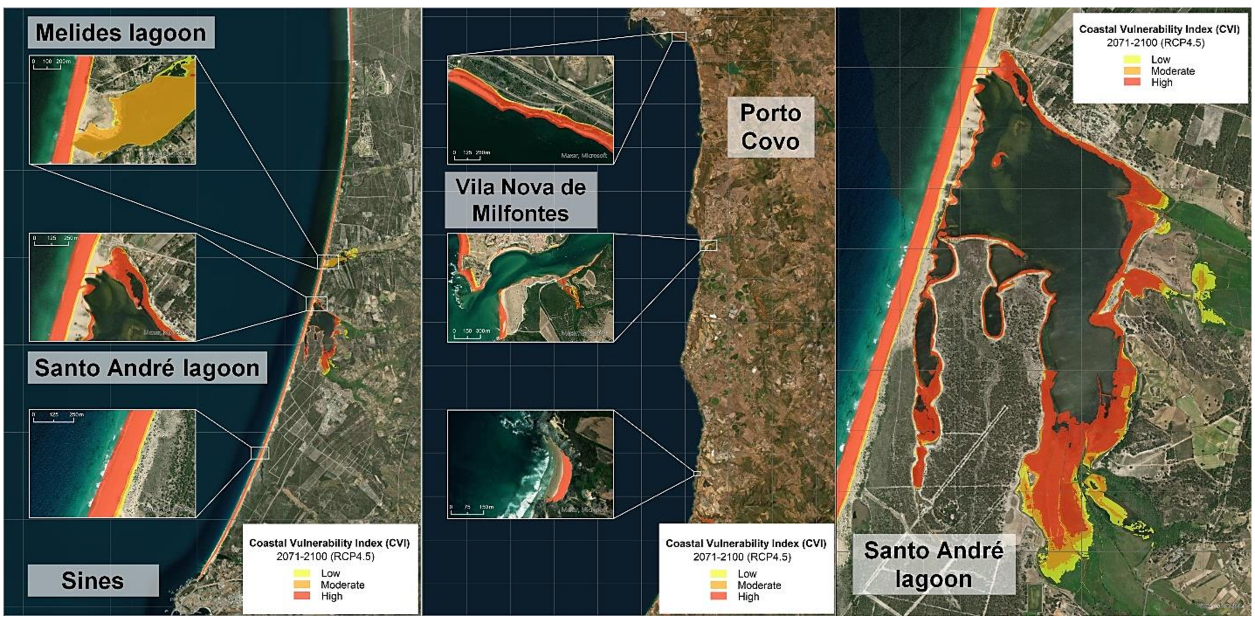


Figure 2.71 – Projected vulnerable areas along the Alentejo region by the end of the 21st century (2071-2100) under RCP4.5, with focus on two different stretches of coast, from Comporta to Sines, and Sines to Odemira, highlighting the Santo André coastal lagoon. The CVI is inversely related to the TWL 4-, 25- and 100-years return period values (*e.g.*, a high CVI is given to coastal areas projected to become flooded under a 4-year RP TWL).

Table 2.45 – Area (in km²) of the vulnerable coastal stretches in the Alentejo region (grouped for the three classes of vulnerability), by the end of the 2041-2070 and 2071-2100 future periods, under both RCP4.5 and RCP8.5 scenarios.

Vulnerable coastal areas (km²)				
Alentejo region	2041-2070		2071-2100	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5

Ocean-facing	7.9	8.8	10.5	9.8
Inland	198.8	200.8	206.5	212.9
Total	206.7	209.6	217.0	222.7

Accounting for the diverse coastal typologies of the Alentejo region (Figure 2.72), a single common adaptation narrative is not obtainable. Narratives have, instead, to be built for each of the multiple coastal environments. Therefore, Figure 2.76 depicts, schematically, the proposed adaptation pathways along the five identified coastal environments in Alentejo. For each one, different pathways are shown, spanning from the present time until the end of the 21st century, and varying due to: (1) each coastal environment's expected response to changes in total water levels and wave characteristics (if facing the ocean), (2) the different possibilities in terms of adaptation strategies, and (3) any site-specific adaptation effort that was already carried in the recent past.

Low-lying sandy beaches
(e.g., Troia to Sines)

Pocket beaches and rocky cliffs
(e.g., Porto Covo – Praia da Samoqueira)

Urban beaches
(e.g., Sines – Praia Vasco da Gama)

Inland waters
(e.g., Sado River estuary)

Figure 2.72 – Different coastal environments in the Alentejo NUTSII region. Specific adaptation pathways are built for each environment in Figure 2.76.

Considering the overall low population density along the Alentejo coastline, and the inexistence of large population centers in the area except for Sines and Alcácer do Sal, adaptation measures are more limited within the region. Historically, artificial beach nourishment has been only carried out in a couple of locations (*e.g.*, Zambujeira do Mar and Troia, the latter for the preservation of roman infrastructure, using sediments dragged for the construction of the new Troia's marina; Figure 2.74). The future strategy is projected to remain similar, *i.e.*, with very localized interventions, greatly depending on the beaches' economic or natural value, instead of the urgent need to protect local populations from SLR and wave-induces erosion. It should be noted, nevertheless, that pocketed beaches, essentially between Sines and Odeceixe (*e.g.* Samoqueira, Porto Covo, Malhão, Almograve, Tonel, Zambujeira do Mar, Amália), are projected to disappear or be extensively reduced towards the end of the 21st century, if no adaptation measures are considered, due to long-term SLR-induced shoreline retreat and the absence of further accommodation on the base of the rocky cliffs.

The accommodation of relevant structures (such as seawall, tidal dykes and harbour structures; Figure 2.74) is considered a viable option protect the urbanized and economically relevant areas, not only along the ocean-facing coastlines (*e.g.* Sines) but also the ones facing inland waters (*e.g.* Alcácer do Sal). Such measure is projected to become increasingly relevant after the middle of the 21st century, although the increased sensitivity of the low-lying areas surrounding the inland waters of the Sado River estuary may require a prioritized approach (as soon as by the 2040s). The required topographic height (relative to the National Vertical Datum CASCAIS1938) for the coastal protection structures to withstand the future projected extreme coastal events[68] is set at 8.09 m, under the intermediate RCP4.5 scenario (Figure 2.73). Excluding wave action, the required height for inland waters coastal protection structures is set at 3.05 m, in order to sustain a 100-year return period event by the end of the 21st century. Departing from the RCP4.5, on a trajectory closer to the RCP8.5, an increase of up to 0.15 m (3.05 m → 3.20 m) is expected for the structures' heights facing inland waters, and an increase of up to 0.13 m (8.05 m → 8.18 m) is expected for the ocean-facing ones. These values should be considered as references to all ocean-facing and inland waters coastlines of the Alentejo region. Note, nevertheless, that coastal stretches with steeper slopes, usually present at highly anthropized ocean-facing segments (*e.g.*, Sines harbour), may expect higher run-up values.

[68] Considering a 99th percentile wave energy event over a 25-year TWL return value.

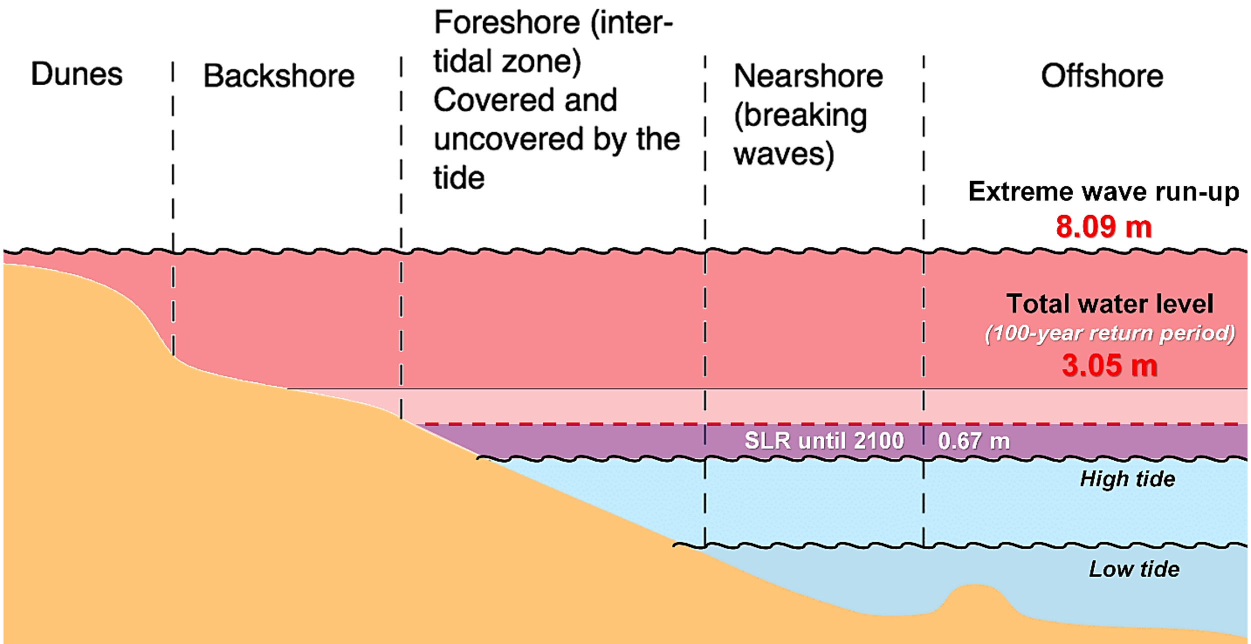


Figure 2.73 – Schematic depiction of how changes in total water levels and run-up may lead to coastal flooding. Note that while for inland waters the maximum coastal flooding topographic height is projected to be set at 3.05 m, for ocean-facing coastlines the value is projected to be set at 8.09 m (values for the RCP4.5 scenario by the end of the 21st century).

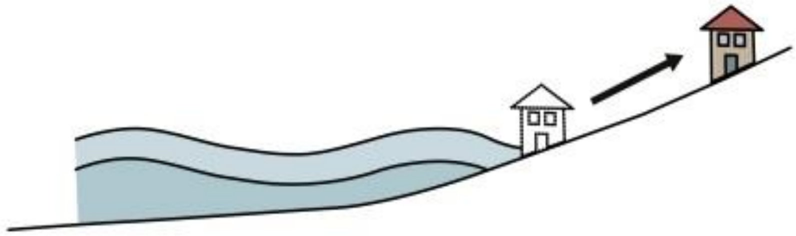
While accommodation of relevant structures such as tidal dykes (in the Sado River estuary) may still be a viable option towards the end of the 21st century, planned relocation actions (Figure 2.74) should become a locally cost-effective way to deal with continuously rising sea levels and extreme coastal flooding, especially along the northern half of the Alentejo's coastline (Figure 2.76; Table 2.46). Bear in mind that for future successful relocation actions, the demolition of exposed illegal or non-essential structures should be prioritized, as it was conducted recently near Melides coastal lagoon. Further South, the rocky cliffy configuration of the domain southbound from Sines is considered to be enough to protect local populations from changes in the sea levels. Nevertheless, without continuous artificial nourishment interventions (which should be considered as a local option – and not a generalized one – if the economic or natural value of the beach justifies it), the pocketed beaches are projected to disappear or be extensively reduced towards the end of the 21st century.

Artificial nourishment

Nature-based solutions for dune rehabilitation and preservation

Cliff stabilization

Demolition of exposed illegal or non-essential structures



Planned relocation

Figure 2.74 – Examples of adaptation measures to be applied in the Alentejo region, and present in the proposed adaptation pathways of Figure 2.76.

The demographic and cost-benefit analysis performed for the Alentejo region is expressed in Table 2.46. Under the RCP4.5 scenario, 838 habitants (according to the CENSOS2021) are projected to become vulnerable[69] until the end of the 21st century, from over 600 vulnerable buildings. Total inaction costs related to patrimonial losses (without adaptation measures; TIC) top at over 195 and 237 million € by 2070 and 2100, respectively, for all coastlines (both inland and ocean-facing ones). The portion of the TIC associated to each coastal municipality of the Alentejo region is depicted in Figure 2.75. Total adaptation costs (TAC), calculated exclusively for ocean-facing coastlines, are estimated at over 726 and 1165 million €, exceeding both the total TIC, and the ones for the same coastlines (91 and 108 million €). In the Alentejo region, the TAC largely outweigh the TIC, being the region with the lowest cost-benefit ratio. Nevertheless, it should be noted that most of the adaptation costs along the Alentejo coastline are associated to the Sines harbor (~700 and ~1100 million € until 2070 and 2100, respectively), and that the indirect value of this vital infrastructure is not represented in the TIC (the reader is referred to the WP5 Adaptation Needs report). The Sines harbor, which represented 1.5% of the Portuguese economy in 2020, could, by itself, be responsible for a quick increase in the projected TIC, if its operations were to be affected by episodic extreme events. Therefore, fostering adaptation strategies is still recommended for the Alentejo region, even though their application may assume a very localized character.

Table 2.46 – Demographic (number of vulnerable residents and buildings projected as vulnerable, *i.e.*, under CVI) and economic cost analysis considering the total inaction costs (TIC) and the total adaptation costs (TAC) in the Alentejo region, by 2070 (end of the 2041-2070 period) and 2100 (end of the 2070-2100 period), under the RCP4.5 scenario.

Alentejo region (RCP4.5 scenario)	2070	2100
Number of residents under CVI	739	838
Number of buildings under CVI	520	652
TIC from 2024 onwards – maximum (M€)	195.6	237.5

[69] *i.e.*, exposed to at least a 100-year return period flooding event.

TIC from 2024 onwards – maximum for ocean-facing coastlines (M€)	91.1	107.7
TAC from 2024 onwards for ocean-facing coastlines (M€)	726.4	1165.1
Annualized maximum TIC (M€/year)	4.2	3.1
Annualized maximum TIC for ocean-facing coastlines (M€)	1.9	1.4
Annualized TAC for ocean-facing coastlines (M€/year)	15.5	15.1

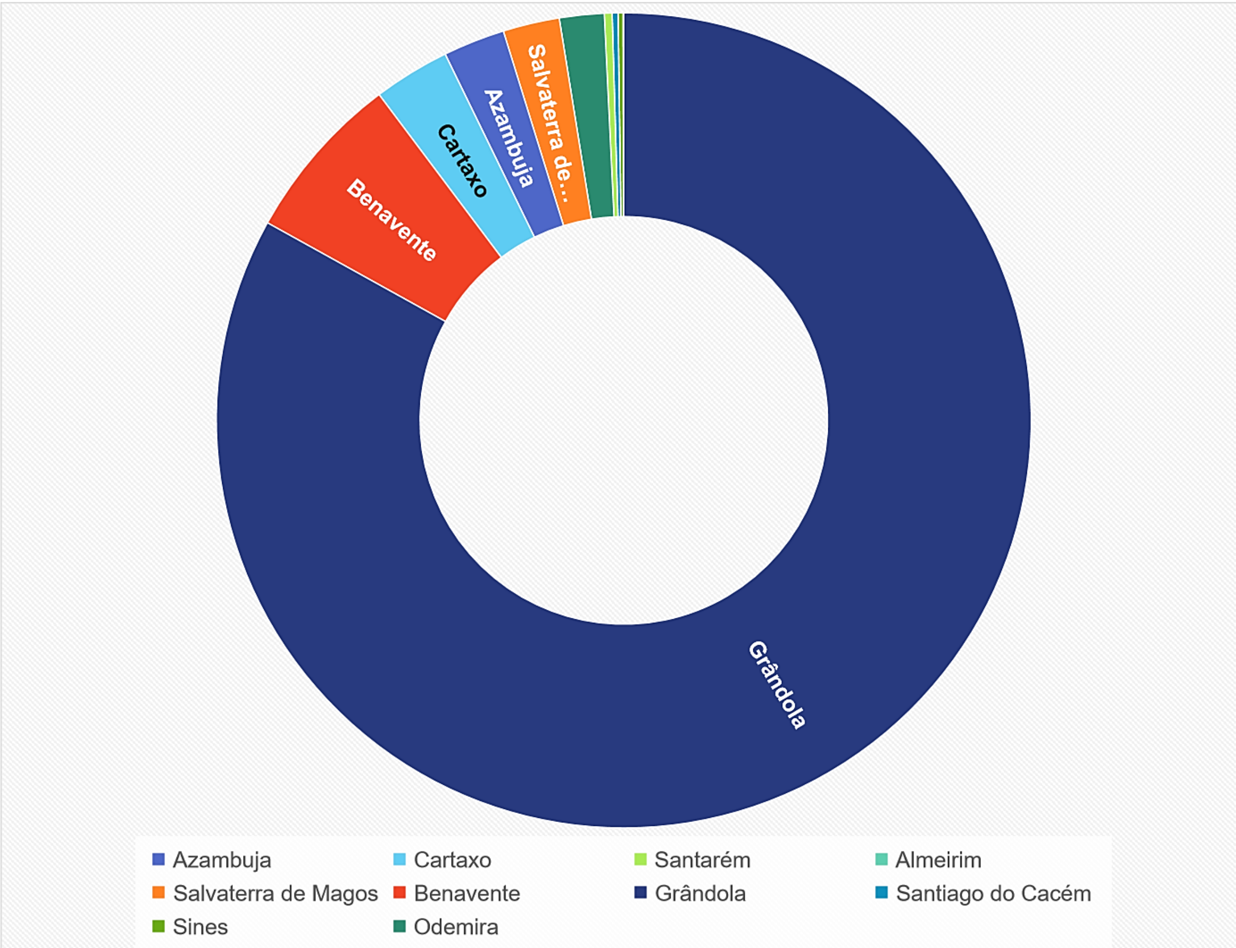


Figure 2.75 – Portion of the TIC (until 2100 under RCP4.5) associated to each coastal municipality of the Alentejo region.

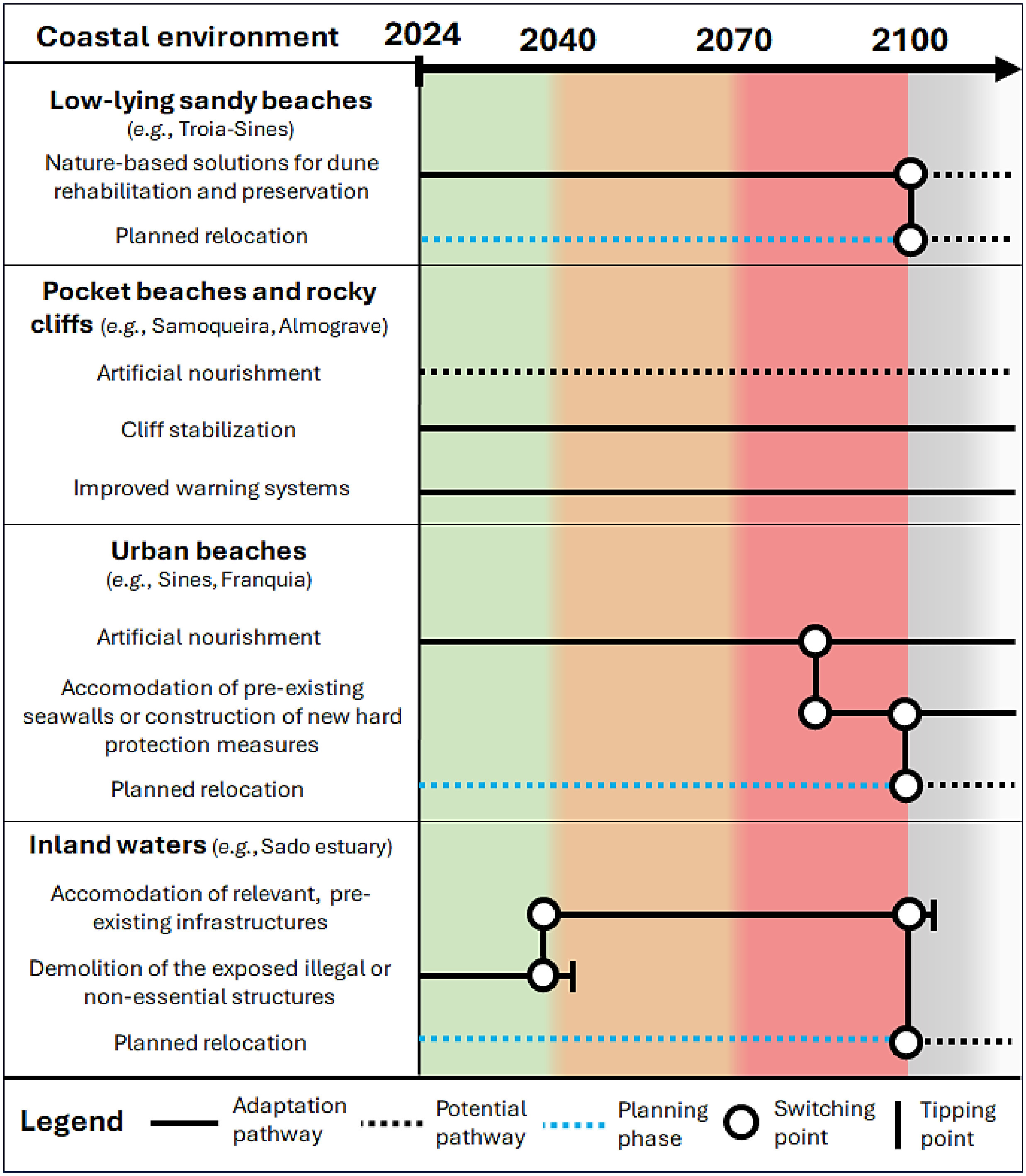


Figure 2.76 – Proposed adaptation pathways along the five identified environments present in the Alentejo NUTSII region, departing from the year 2024, and spanning until the end of the 21st century. The pathways in full correspond to the most viable adaptation strategy for each coastal environment.

2.4.4. Forest fires

The Alentejo region in Portugal (Figure 2.77) experiences a predominantly Mediterranean climate with some variations due to its vast size and diverse geography. Generally, the climate is characterized by hot, dry summers and relatively cold winters. However, there are heterogeneities within the region, particularly regarding temperature, precipitation, and wind patterns. Odemira, located within the Alentejo region, is known for its susceptibility to wildfires, particularly during the summer months. Several factors contribute to this propensity. Odemira experiences high temperatures during the summer, often exceeding 30°C. Coupled with low relative humidity, these conditions promote the drying of vegetation, making it more prone to ignition. The region's landscape consists of a mix of forests, scrubland, and agricultural areas. During the summer, vegetation can become desiccated, providing ample fuel for wildfires. Winds play a significant role in wildfire behaviour. Odemira and surrounding areas can experience strong winds, particularly from the north and northwest. These winds can quickly spread fires, making them difficult to control. Serra de São Mamede, located in the Portalegre District of Alentejo, shares some similarities with Odemira in terms of wildfire risk. Serra de São Mamede is characterized by rugged terrain, including hills and mountains, which can influence local weather patterns and fire behaviour. Like Odemira, Serra de São Mamede has a diverse mix of vegetation types, including forests and shrublands. Dense vegetation, combined with dry conditions, increases the likelihood of wildfires. The region experiences hot and dry summers, with minimal rainfall. These conditions create an environment conducive to the ignition and spread of wildfires. Overall, both Odemira and Serra de São Mamede are vulnerable to wildfires due to their climatic conditions, vegetation characteristics, and topography. Efforts to mitigate wildfire risk in these regions typically involve preventive measures such as land management practices, firebreak construction, and public awareness campaigns.

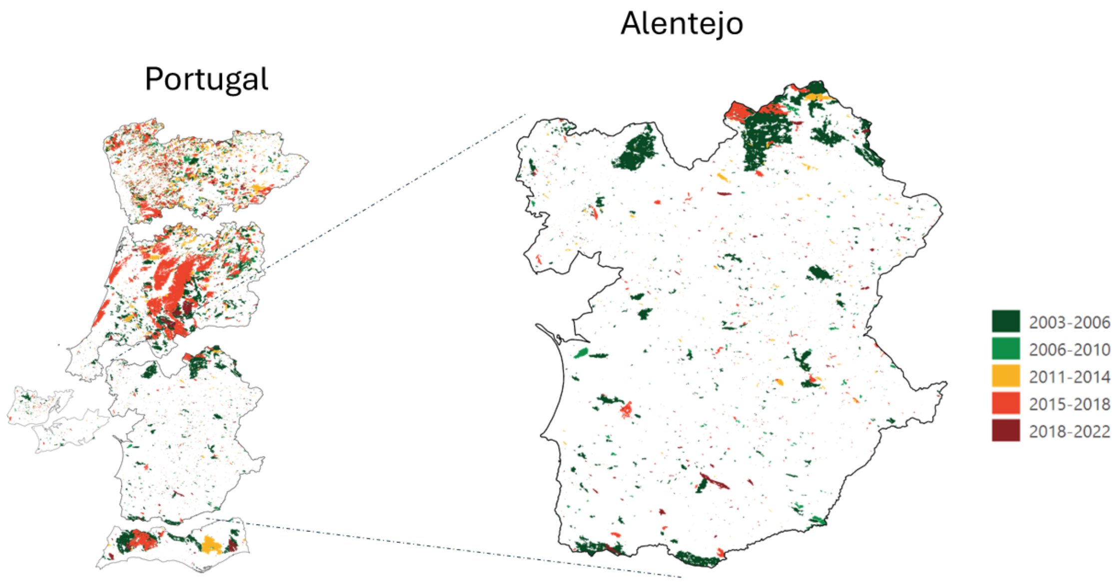


Figure 2.77 – Highlight of Alentejo burned area, with the colours representing the period where the last occurrence took place.

Meteorology is key in defining the composition and structure of vegetation fuels but also holds a central position in determining the susceptibility of these fuels to fire. Human activities and vegetation management practices contribute to the present state of vegetation fuels, while their typology is intricately linked to the broader ecological domains they inhabit. Weather effects exert a profound influence on the vulnerability of vegetation fuels to ignition. They can control the moisture content of different fuels, enabling rapid wetting or drying of fine fuels such as litter, needles, mosses, and twigs. The response is comparatively slower for coarser wooden fuels. The moisture levels in these various fuels, coupled with meteorological factors like wind speed, collectively influence the ease of ignition, potential propagation, and severity of a fire. Recognizing the pivotal importance of meteorology in fire danger assessment is imperative for developing effective strategies for wildfire preparedness and adaptation. A comprehensive understanding of how meteorological conditions interact with other factors contributes significantly to the ability to predict and manage wildfires. Forest management practices, such as prescribed burning, fuel reduction treatments, and landscape-scale planning are essential for reducing fire risk and enhancing ecosystem resilience. Integrating these practices with other fields of expertise, such as ecology, hydrology, and land-use planning, can help optimize adaptation strategies and minimize trade-offs between conservation and fire management objectives. The Alentejo region values its forests for the multitude of ecosystem services they provide, including carbon sequestration, biodiversity conservation, soil stabilization, and water regulation, contributing significantly to the region's environmental health and sustainability.

Meteorological forecasts and early warning systems are critical tools for mitigating fire risks and facilitating timely response efforts. Enhanced monitoring technologies, such as remote sensing, GIS mapping and decision support systems, provide valuable data and insights for fire management decision-making. However, implementing these strategies requires overcoming various challenges, including limited funding, conflicting land-use priorities, regulatory constraints, and social resistance. Addressing these barriers and fostering collaboration between government agencies, non-profit organizations, private landowners, and local communities is essential for effective wildfire management in the Alentejo region.

Hence, the future meteorological danger was assessed by taking advantage of the enhanced Fire Weather Index (FWIe)[70]. It is projected a significant increase in the number of extreme fire danger days (Table 2.47), i.e., the number of days where FWIe is extremely high. For the RCP4.5 more 12 (14) days in extreme fire danger for the mid- (end-) century are projected with respect to the historical values; slighter changes for the RCP2.6 are projected, from additional + 5 to +4 days, and for the RCP8.5 the number of extreme fire danger can escalate more +29 at the end of the century, more than tripling the 15-days mark observed in the historical climate.

Table 2.47 – Additional number of days per extended summer (June to September) with extreme fire danger for different emission scenarios compared to the present climate.

Alentejo	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Additional days (present climate = 15 days)	+5	+12	+16	+4	+14	+29

The 2023 Odemira wildfire (Figure 2.78) affected 8,400 ha and resulted in estimated losses of 10 million euros, which corresponds to about 1,190 euros/ha. This highlights the urgent concern about the potential tripling of days with extreme meteorological danger in the region. In the current climate context, assuming similar losses per ha, the cumulative financial toll of forest fires over the past 20 years stands at around 329 million euros, i.e., about 16.5 million euros/year.

[70] The enhanced FWI is a meteorological fire danger index that combines an atmospheric instability parameter.

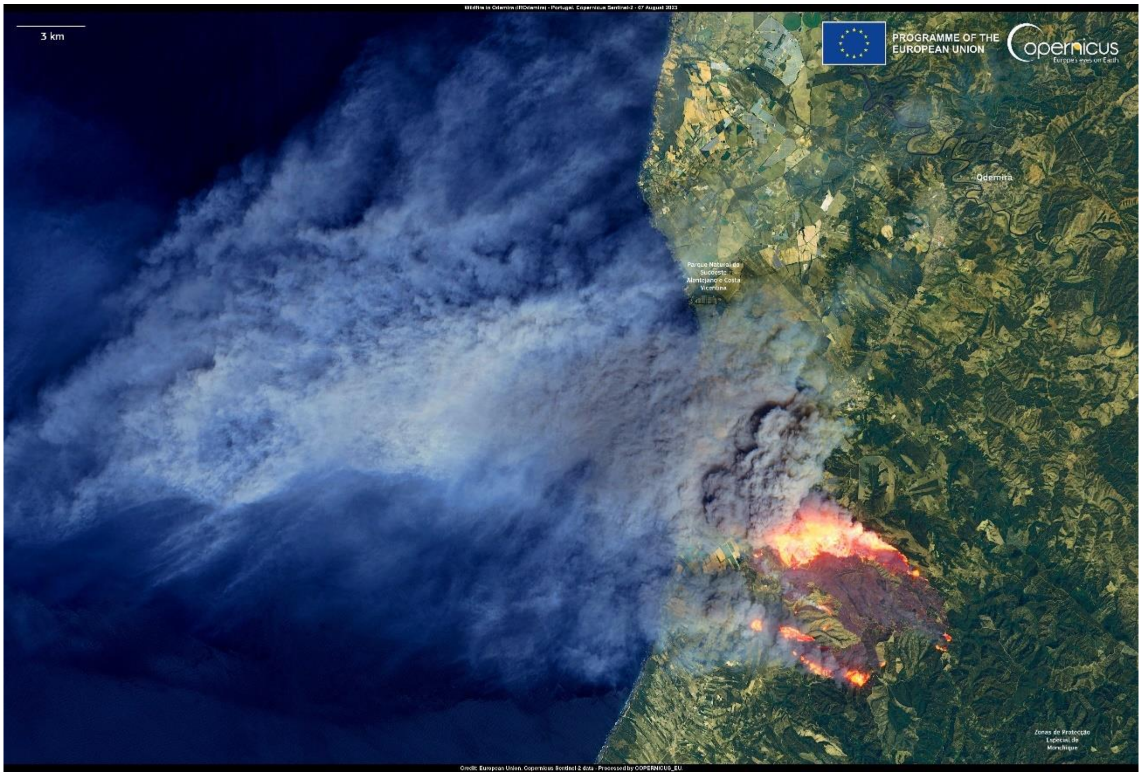


Figure 2.78 – Hotspots and the massive smoke cloud generated by the 2023 Odemira wildfire reaching the Atlantic Ocean (Credit: European Union, Copernicus Sentinel-2 imagery).

From the probabilistic model developed in the context of RNA2100, it is possible to estimate that the likelihood of having forest fires of similar intensity as the 2023 Odemira event can be near 2 times the historical frequency, in agreement with the probability of exceedance of a given fire radiative power under the RCP4.5. Without proactive adaptation measures, the projected losses (Table 2.48) could escalate to nearly 31 million euros/year under RCP4.5 (almost doubling the 16.5 million euros/year mark).

Table 2.48 – Projected losses without implementing adaptation measures, in million euros/year for Alentejo.

Alentejo (No adaptation)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Losses (million euro/year)	30.5	31.3	33.8	24.3	31.3	42.9

In response to the escalating threat of forest fires exacerbated by climate change, it is paramount for the Alentejo region the recognition of the critical importance of implementing adaptation strategies to safeguard its natural landscapes and communities. Drawing upon insights from diverse fields of expertise, including forest management and ecology.

Acknowledging the invaluable role of forest management practices in mitigating fire risk, efforts are underway to implement targeted interventions aimed at reducing fuel loads and enhancing ecosystem resilience. By leveraging knowledge of the region's diverse forest types, which range from cork oak forests to pine stands and Mediterranean scrublands, tailored management strategies can be developed to optimize fire prevention and suppression efforts. This includes prescribed burning, selective thinning and creating strategic firebreaks to interrupt the continuity of fuel and limit fire spread.

Following the objectives of *Roadmap for carbon neutrality 2050 (RNC2050)*, a paramount objective is to significantly decrease the annual burned area to a fraction of its current extent by 2050, marking a substantial reduction. This necessitates meticulous planning for the utilization of post-fire areas, prioritizing reforestation efforts with species resilient to fire and conducive to carbon sequestration, thus preventing deforestation and the conversion of forests into less productive land covers like scrubland. Additionally, adopting effective fire prevention measures, such as utilizing small ruminants to manage combustible materials, is crucial to mitigate fire risks and protect forest ecosystems. Enhancing forest management practices is fundamental to augmenting average productivity and resilience. Measures such as optimizing forest management techniques, intensifying fire prevention measures, and selecting more productive and climate-resilient species will lead to increased forest density and carbon sequestration capacity. By focusing on both production and protection species, the health and sustainability of forest ecosystems can be bolstered. Furthermore, accelerating afforestation efforts and curtailing the expansion of non-forest land uses, particularly urbanized areas, floodplains, and scrublands, are essential. By prioritizing afforestation and sustainable land use practices, the Alentejo region can effectively mitigate climate change impacts, enhance ecosystem services, and foster a resilient and sustainable future for both nature and communities.

However, effective adaptation requires more than just forest management; it necessitates a holistic approach that integrates education and awareness initiatives to foster a culture of fire prevention and safety. By engaging individuals of all ages, from school children to adults, in educational programs and outreach campaigns, communities can become active participants in wildfire prevention efforts. Understanding the ecological importance of forests, the risks posed by irresponsible behaviours such as discarded cigarettes or poorly managed outdoor activities, and the importance of adhering to fire restrictions are essential components of building a resilient society in the face of escalating fire risks. In addition to proactive measures, a responsive approach is crucial for addressing immediate threats during periods of extreme meteorological danger. By leveraging advances in meteorological forecasting and early warning systems, authorities can anticipate and prepare for heightened fire risk on days with adverse weather conditions. This requires collaboration across disciplines, including meteorology, climatology, and data science, to develop robust predictive models that integrate real-time data on weather patterns, fuel moisture content, and vegetation stress indicators. The CEASEFIRE[71] platform is an example of such collaboration, with customised weather information for forest fire prevention, planning and fighting. By harnessing this knowledge and technology, decision-makers can make informed decisions about resource allocation, emergency response, and community evacuation, ultimately minimizing the impact of wildfires on lives, property, and ecosystems. While challenges remain in implementing these adaptation strategies, including technical complexities and resource constraints, the collective efforts of stakeholders from various fields of expertise underscore the urgency and importance of proactive climate adaptation in the Alentejo region.

By integrating insights from forest management, ecology, meteorology and education, communities can build resilience to the growing threat of forest fires and ensure the long-term sustainability of their natural environment and way of life. These insights can be put in place under the three types of strategies that were assessed. One focused only on awareness measures, other on awareness and coercive measures, and the last only on coercive measures. Awareness measures cover initiatives such as continuous education and capacitation of the society. On the other hand, coercive measures encompass actions such as targeted fines. These adaptation measures aim to reduce ignitions and the costs related to large wildfires. For example, Figure 2.79 shows the projected losses without adaptation (black bar) and with implementation of adaptation measures (blue, green, and orange bars), in million euros/year for Alentejo. Focusing on RCP4.5, the 16.5 million euros/year mean value may reach 31 million euros/year under climate change, which means an increment of 14.5 million euros/year.

[71] https://ceasefire.pt

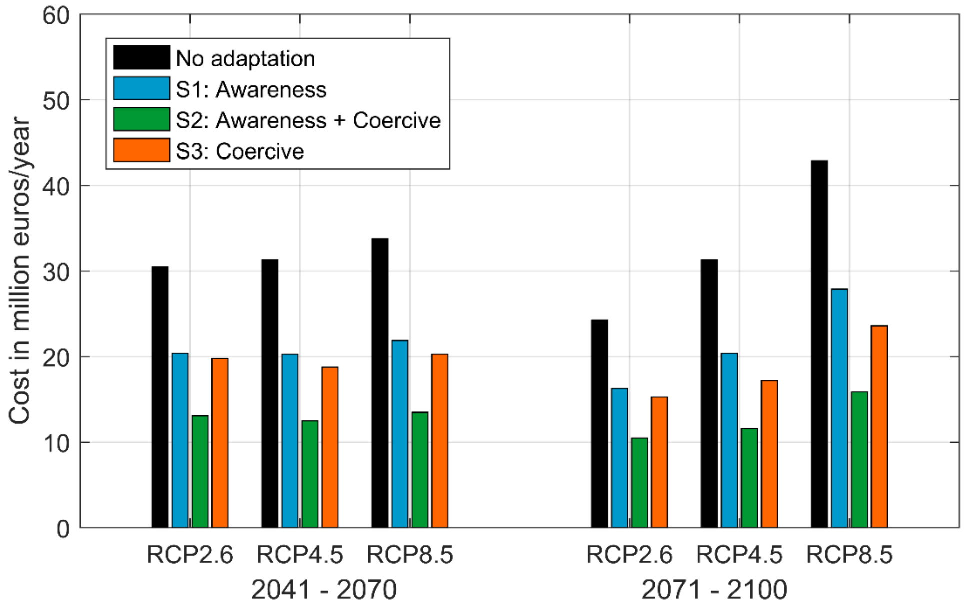


Figure 2.79 – Projected cost of no adaptation (black bar) and cost with implementation of adaptation strategies of Awareness (blue bars), Awareness + Coercive (green bars), and Coercive (orange bars), in million euros/year for Alentejo, under RCP2.6, RCP4.5, and RCP8.5 for the middle of the century (2041 – 2070; left) and the end of the century (2071 – 2100; right).

With a strategy focused on awareness, it is possible to reduce the losses to about 20 million euros/year. It is however important to note that with the advancement of time, climate change will severely impact the number of days in extreme danger, and consequently coercive strategies to reduce the number of ignitions and consequently burned area may be used. These strategies can represent savings of 11 million euros/year. However, it is essential to note that a pathway focused on both awareness and coercive strategies brings better results, even decreasing the annual cost of the last 20 years to about 12 million euros/year, representing savings of the order of around 19 million euros/year. Figure 2.80 shows the adaptation pathway for Alentejo focused on RCP4.5. Several adaptation and mitigation strategies were already implemented and are expected to continue being implemented in the coming years. Awareness strategies should be first implemented to alert and educate society to the perils of climate change and its impact on forest fires. Eventually, in the most dangerous periods, coercive strategies should be implemented. However, with the increase in global warming, a mix between awareness and coercive continuous strategies must be implemented to prevent tragedies such as the 2023 Odemira fire to become the new normal.

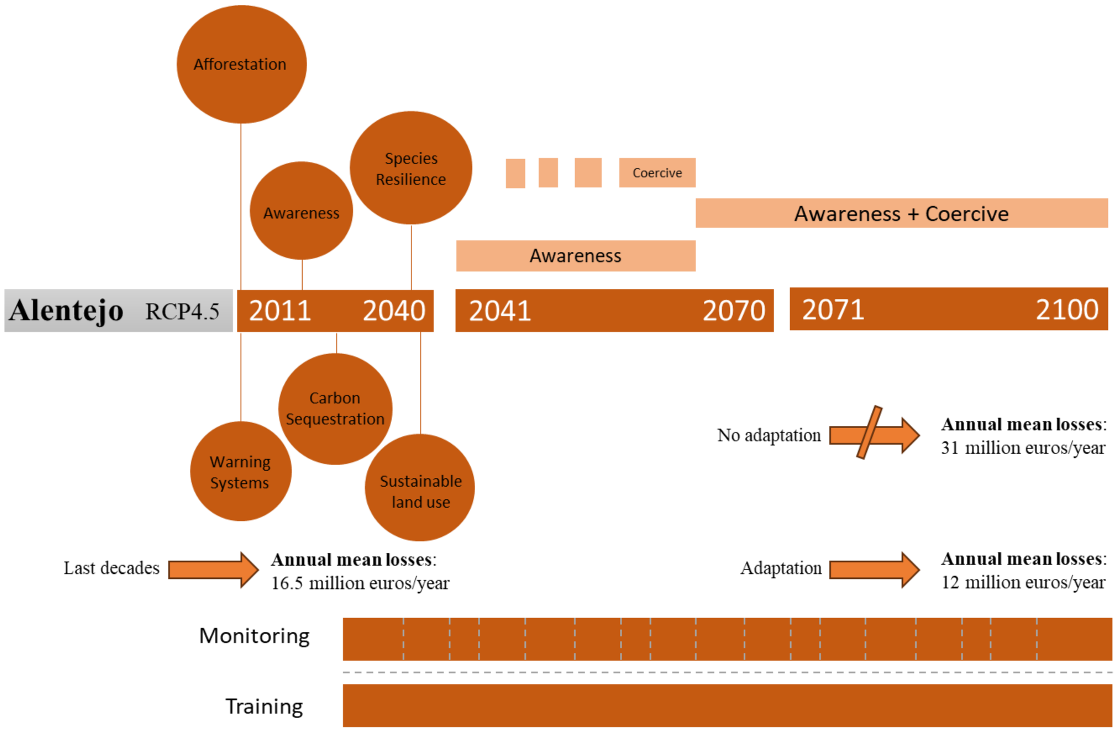


Figure 2.80 – Adaptation narrative for forest fires sector until 2100 for Alentejo under RCP4.5.

2.5. Algarve

2.5.1. Climate projections

The Algarve region is projected to experience more significant warming compared to the global average (Figure 2.81 and Table 2.49). Projections indicate a more pronounced warming in summer than in winter across all climate scenarios. In the RCP4.5 scenario, the Algarve region is projected to undergo a temperature rise of +1 to +2.5 ºC. Even under the RCP2.6 scenario, an increase in annual temperature of +1 to +2 ºC is expected during the 21st century. Under the RCP8.5 scenario, temperature increases of +4.1 ºC and +4.8 ºC are projected by the end of the 21st century respectively for maximum and minimum temperatures.

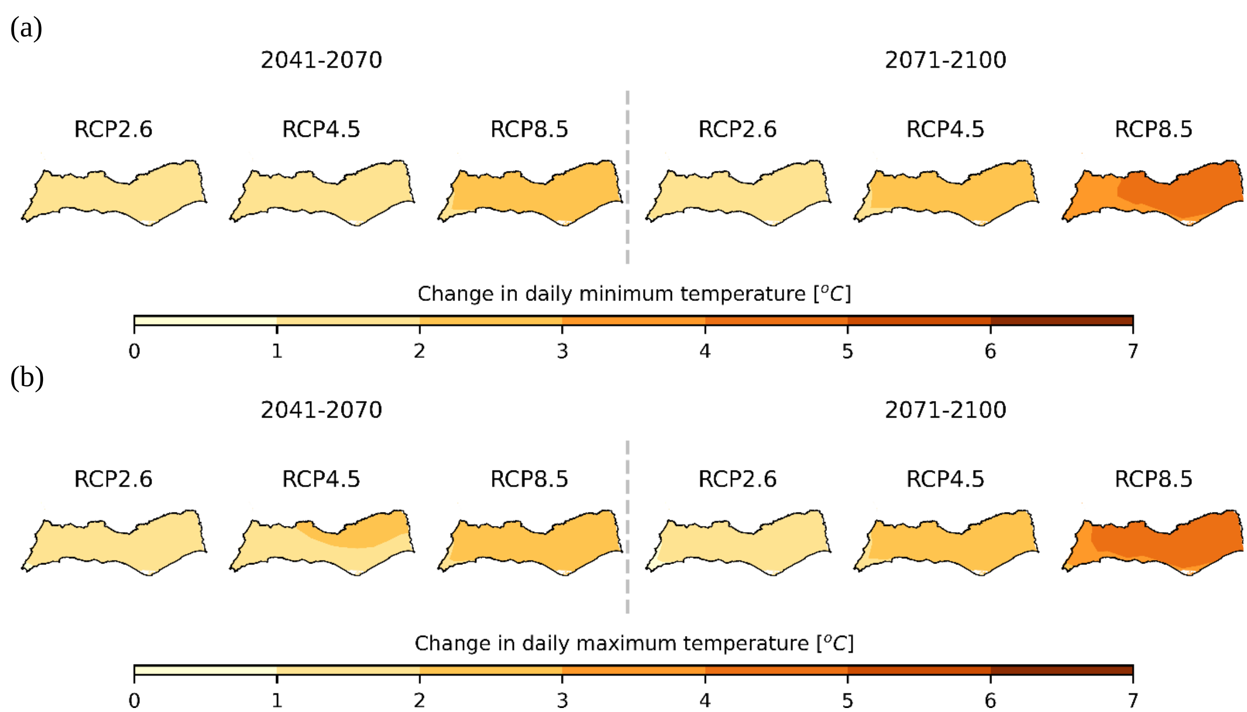


Figure 2.81 – Future projected changes in daily (a) minimum and (b) maximum temperature (°C) for the Algarve NUTS II region.

Table 2.49 – Climatological annual mean daily minimum (Tn) and maximum (Tx) temperature (°C) for the reference period (Historical – 1971-2000); and, future projected changes in daily minimum and maximum temperature (°C) for the Algarve NUTS II region.

Algarve	1971-2000	Differences	2041-2070			2071-2100		
	Historical		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
T_n (°C)	11.2	ΔT_n (°C)	1.4	1.8	2.4	1.3	2.3	4.1
T_x (°C)	21.3	ΔT_x (°C)	1.4	1.9	2.6	1.2	2.5	4.4

Changes in precipitation are greatly dependent on the season and the future emission scenario. Future projections suggest a decline in mean precipitation across the 21st century, indicating a rise of aridity in

Algarve (Figure 2.82 and Table 2.50). Significantly, the RCP4.5 scenario portrays a distinct decline in annual precipitation, with projected reductions of around -20% by the end of the 21st century. For the RCP2.6 scenario, the precipitation changes are small, fluctuating within -5% and +5%. For the RCP8.5 scenario, the projections point to an annual precipitation reduction exceeding -30% by the end of the century. Independently of the emission scenario, the decline of precipitation predominantly occurs in spring, summer and autumn.

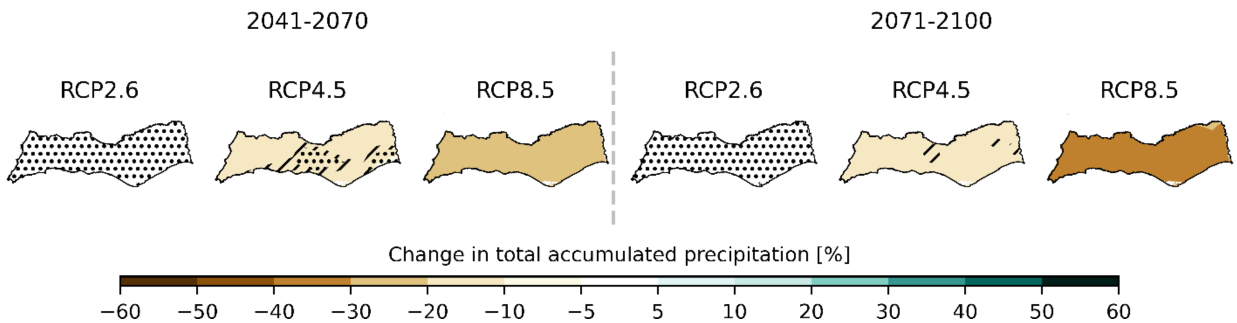


Figure 2.82 – Future projected relative changes in annual accumulated precipitation (%) for the Algarve NUTS II region. Grid-points where the precipitation does not specify changes statistically significant are identified by dotted hatching.

Table 2.50 – Climatological annual mean accumulated precipitation (Pr) (mm) for the reference period (Historical – 1971-2000); and, future projected relative/absolute changes in annual accumulated precipitation (%/mm) for the Algarve NUTS II region.

Algarve	1971-2000	Differences	2041-2070			2071-2100		
	Historical		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
$Pr\ (mm)$	617.6	$\Delta Pr\ (\%)$	-2.6	-13.5	-22.9	2.5	-17.5	-33.4
		$\Delta Pr\ (mm)$	-10.8	-80.7	-138.9	18.5	-107.9	-205.3

As a result of the warming, the frequency and intensity of extreme temperature events will undergo changes, which are less (more) pronounced under the RCP2.6 (RCP8.5) scenario (Figure 2.83). Concurrent with the rise in maximum temperatures, the occurrence of hot days[72], as well as summer[73] and extremely hot days[74], is projected to rise. In the historical period (1971-2000), the number of hot days ranges between 20 and 80 days from littoral to inland. For the RCP4.5, more 40 hot days are expected at the end of the century. For the RCP2.6, the increase is close to 20 days, but for the RCP8.5 the number of hot days is projected to duplicate when compared to the historical period, with more additional 60 hot days per year. Furthermore, heatwaves[75] are projected to become more frequent, intense, and longer lasting. In the historical period approximately 1 to 2 heatwaves occur per year with a mean duration around 6 days per event. Under the

72 Hot days: number of days where maximum temperature exceeds 30ºC.
73 Summer days: number of days where maximum temperature exceeds 25ºC.
74 Very hot days: number of days where maximum temperature exceeds 35ºC.
75 Heatwave is defined as a period of five or more consecutive days with maximum temperature above the 90th percentile.

RCP4.5, it is expected an increase in the number of heatwaves between 4 and 5 throughout the 21st century. Even under the RCP2.6, the occurrence of 3 heatwaves per year is projected. However, considering the RCP8.5, the projections point to more 10 heatwaves per year. Aligned with the increase in the number of heatwaves, the mean duration of these events is also projected to increase. For the RCP4.5, the mean duration of heatwaves is projected to increase around 2 days. A similar result is expected for the RCP2.6, whilst under the RCP8.5, the expected increase is between 3 and 5 more days in heatwave, when compared with the historical period. Aligned with the rising of minimum temperature, tropical nights[76] are expected to become more prevalent, while the incidence of cold days[77] will diminish. For the RCP4.5 the number of tropical nights is projected to increase up to more 40 nights per year, and for the RCP8.5 the projected changes may reach up to more 80 nights per year.

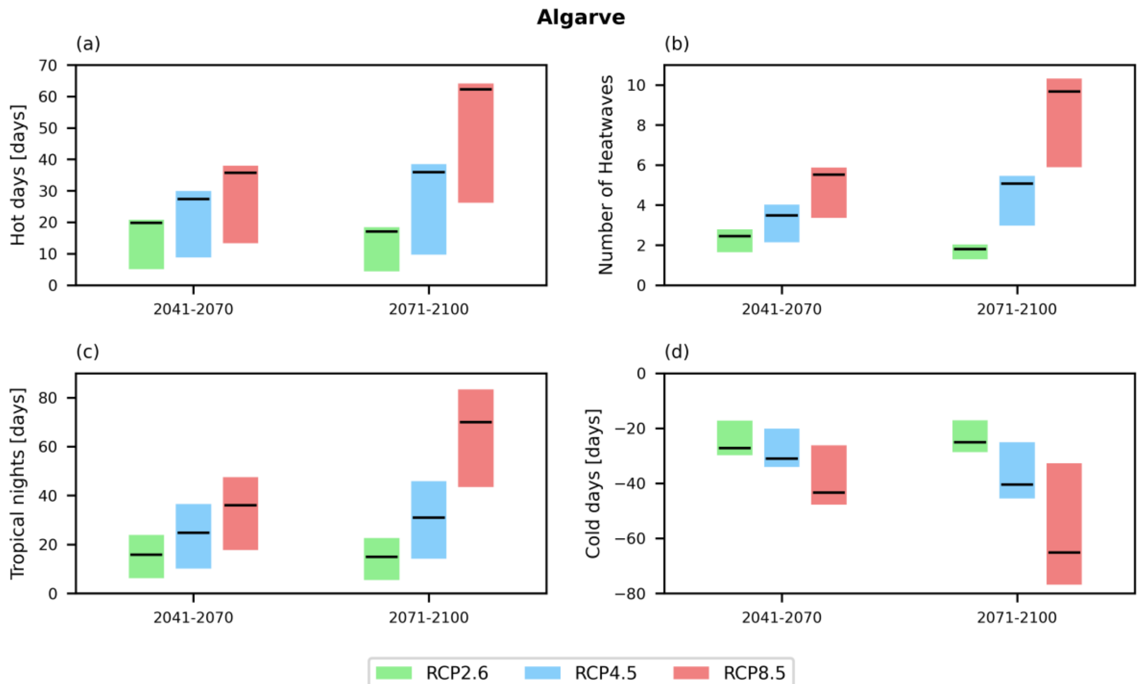


Figure 2.83 – Distribution of the projected changes in (a) hot days [days/year], (b) number of heatwaves per year, (c) tropical nights [days/year] and (d) cold days [days/year] for all gridpoints in Algarve's region. The straight black line represents the mean value for the Algarve's region. Individual boxes span from the spatial minimum to the maximum value of the Algarve's region.

In line with the decline in mean accumulated precipitation, a reduction in the number of wet days[78] and, consequently, an increase in the number of dry days, is projected until the end of the 21st century (Figure 2.84). For the RCP4.5 scenario, less 10 wet days is projected throughout the 21st century. For the RCP2.6 scenario, however, are expected negligible changes throughout the century, with a slight decrease during

[76] Tropical nights: number of days where minimum temperature exceeds 20ºC.
[77] Cold days: number of days where minimum temperature is below 7ºC.
[78] Wet days: number of days with precipitation exceeding 1 mm/day.

the mid- and end-21st century around 4 wet days. For the RCP8.5 scenario, the projections point to less 27 wet days at the end of the 21st century. Consequently, the number of consecutive dry days[79] is expected to increase, enhancing drying conditions. Regarding the number of days with moderate[80] and heavy[81] precipitation, clear projected reductions are evident, especially under the RCP4.5 and RCP8.5 scenarios. The maximum 5-day accumulated precipitation[82] is projected to increase along the coast and over the western area of Algarve's region. Under the RCP4.5 scenario, the increases can reach more 20 mm (in the historical period the maximum 5-day accumulated precipitation value is around 200 mm). The projections for the RCP2.6 scenario are both positive and negative, being the mean changes quite negligible. For the RCP8.5 scenario, the increase of maximum 5-day accumulated precipitation can reach more 30 mm. In spite of the projected decrease of the number of wet days, projections suggest a concentration of rainfall into shorter time frames, implying an intensification of moderate/heavy precipitation regardless of the scenario.

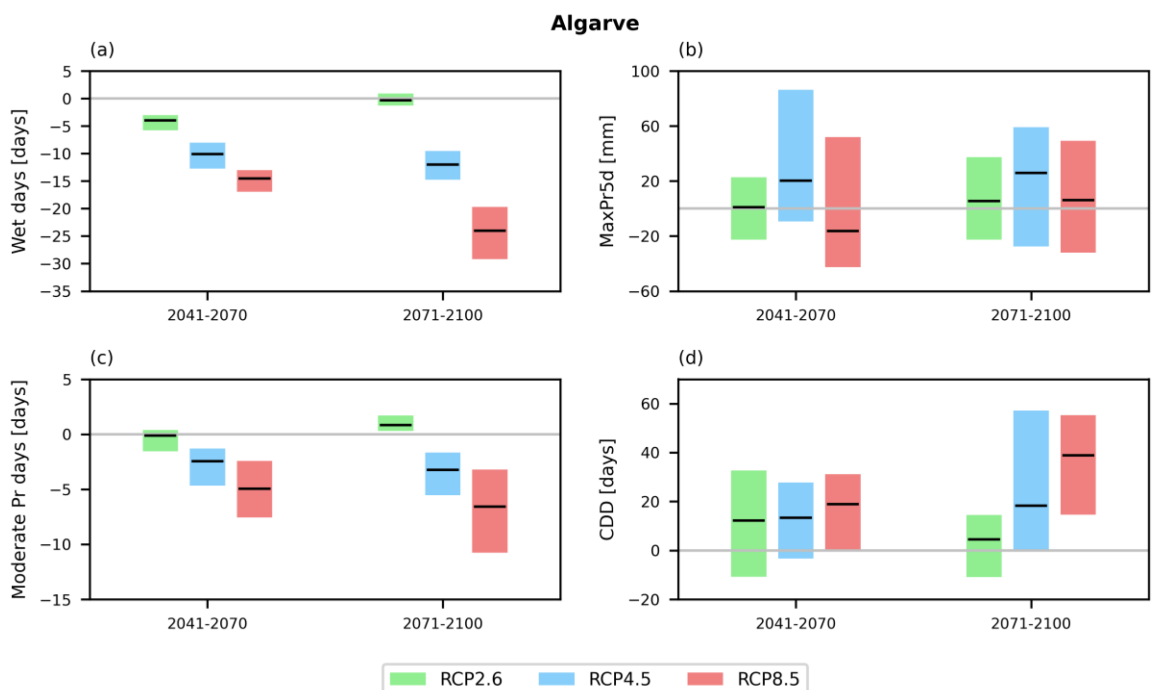


Figure 2.84 – Distribution of the projected changes in (a) wet days [days/year], (b) maximum of 5-day accumulated precipitation (MaxPr5d) [mm], (c) moderate precipitation days [days/year] and (d) consecutive dry days (CDD) [days] for all gridpoints in Algarve's region. The straight black line represents the mean value for the Algarve's region. Individual boxes span from the spatial minimum to the maximum value of the Algarve's region.

[79] Dry days: number of maximum consecutive dry days where precipitation is below 1 mm/day.
[80] Moderate precipitation days: number of days with precipitation exceeding 10 mm/day.
[81] Heavy precipitation days: number of days with precipitation exceeding 20 mm/day.
[82] Maximum of 5-day accumulated precipitation.

A summary of confidence in the direction of projected changes in climate means and indices is presented in Table 2.51. The results give us confidence in climate projections presented here.

Table 2.51 – Summary of confidence in the direction of projected change in climate means and indices for the Algarve NUTS II region. Temperature: climatological annual mean daily minimum (Tn) and maximum (Tx) temperature, hot days (Txg30), number of heatwaves per year (HWN), tropical nights (Tng20) and cold days (Tnl7); Precipitation: climatological annual mean accumulated precipitation (Pr), wet days (Prg1), maximum of 5-day accumulated precipitation (MaxPr5d), moderate precipitation days (Prg10) and consecutive dry days (CDD). A standard deviation of 0.25, 1, 2, 3 corresponds to a moderate, strong, very strong, severe increase/decrease of the variables. Values shown are ensemble median changes. Colours illustrate the model's agreement within the multi-model ensemble.

Algarve							
		2041-2070			2071-2100		
		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Temperature	Tx	↑↑	↑↑↑	↑↑↑	↑↑	↑↑↑	↑↑↑
	Txg30	↑	↑↑	↑↑↑	↑	↑↑↑	↑↑↑
	HWN	↑↑	↑↑↑	↑↑↑	↑	↑↑↑	↑↑↑
	Tn	↑↑↑	↑↑↑	↑↑↑	↑↑	↑↑↑	↑↑↑
	Tnl7	↓↓	↓↓	↓↓↓	↓↓	↓↓↓	↓↓↓
	Tng20	↑↑	↑↑↑	↑↑↑	↑	↑↑↑	↑↑↑
Precipitation	Pr	⤨	↘	↘	⤨	↘	↓
	MaxPr5d	⤨	↗	↘	⤨	↗	⤨
	Prg1	↘	↘	↓	⤨	↘	↓
	Prg10	⤨	↘	↘	⤨	↘	↓
	CDD	↗	↗	↗	⤨	↗	↑

↑↑↑	Change above 3 standard deviations
↑↑	Change above 2 standard deviations
↑	Change above 1 standard deviation
↗	Change above 0.25 standard deviations
⤨	Change between -0.25 and 0.25 standard deviations
↘	Change below -0.25 standard deviations
↓	Change below -1 standard deviation
↓↓	Change below -2 standard deviations
↓↓↓	Change below -3 standard deviations

	High agreement: at least 80% of models show a positive change
	Low agreement: at least 50% of models show a positive change
	No agreement: models disagree on the direction of change
	Low agreement: at least 50% of models show a negative change
	High agreement: at least 80% of models show a negative change

2.5.2. Water scarcity and stress on crops

NUTS II Algarve includes, within its administrative boundaries, two River Basins: RH8 - Ribeiras do Algarve and RH7 Guadiana (Figure 2.85). The Ribeiras do Algarve River Basin has four public water reservoirs (Bravura, Odelouca, Funcho, Arade), several irrigated areas in operation, of which three stand out for their size: AH Silves, Lagoa and Portimão, AH Sotavento Algarvio and AH Alvor. This has different aquifers, of which Querença-Silves stands out, with about 43% of the water availability coming from this source. The Guadiana River Basin has as its main river the Guadiana, which crosses part of the Portuguese and Spanish territory. This also has two public water reservoirs in the Algarve region (Odeleite and Beliche), and supply water to the AH Sotavento Algarvio.

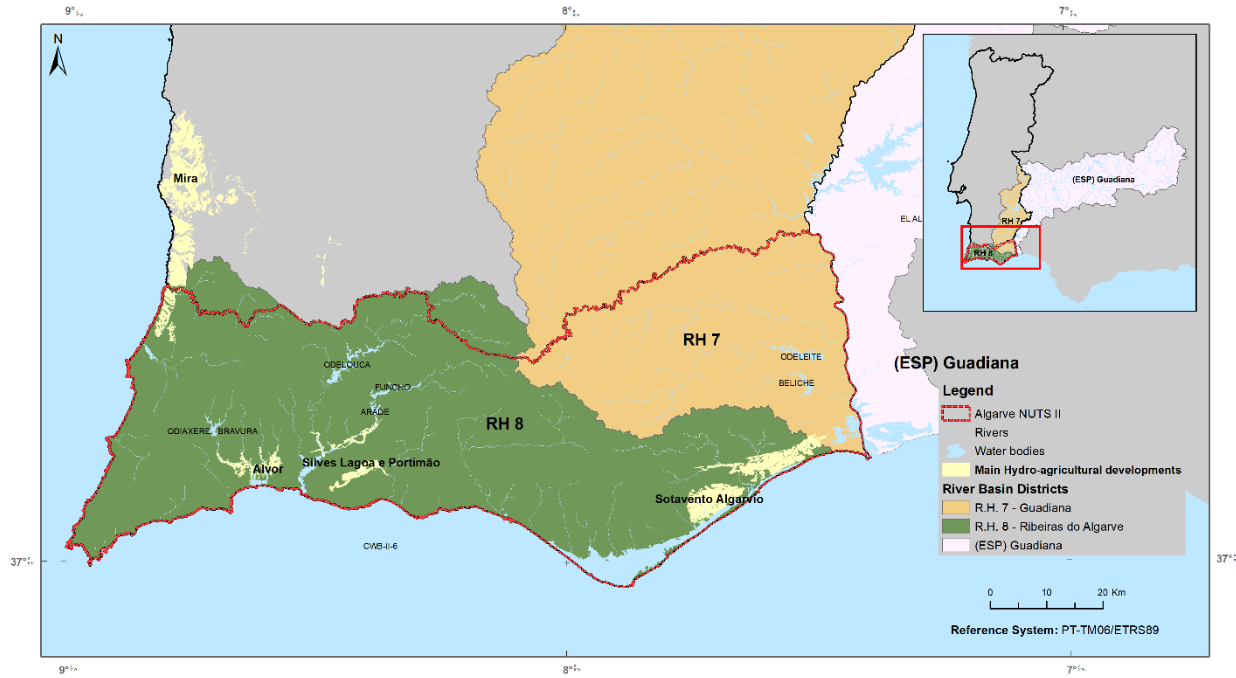


Figure 2.85 – NUTSII Algarve and River Basins Districts location: RH7 Guadiana and RH8 Ribeiras do Algarve.

In 2022, the Algarve region was the leading national producer of citrus, contributing 87% to the country's total production. The most significant crop for regional productivity is oranges, accounting for 71.6% of the total production, followed by forage crops at only 5.3%. There has been a growing importance of avocado production, making it the third most produced crop, representing 5.1% of the total regional production.

However, the region has been facing a severe drought situation in the last years, which has reduced the water levels in the reservoirs, aquifers, and watercourses, with negative impacts on the environment, agriculture, and public supply. This situation is expected to worsen in the future, as climate change projections indicate a decrease in water yield for the RCP4.5 scenario. This trend becomes more pronounced for scenarios with higher concentrations of greenhouse gases in the atmosphere (RCP8.5). However, a slight increase in water yield is projected for the end of the century if concentration levels follow those outlined in the Paris Agreement (RCP2.6) (Figure 2.86). Nevertheless, it is essential to emphasize that this does not necessarily imply a reduction in water stress levels within the region. The dynamics of water stress depend on balancing water availability with demands. The Water Exploitation Index plus (WEI+) is a ratio comparing water use to renewable water resources and serves as a common tool in the European Union and Portugal for assessing this equilibrium.

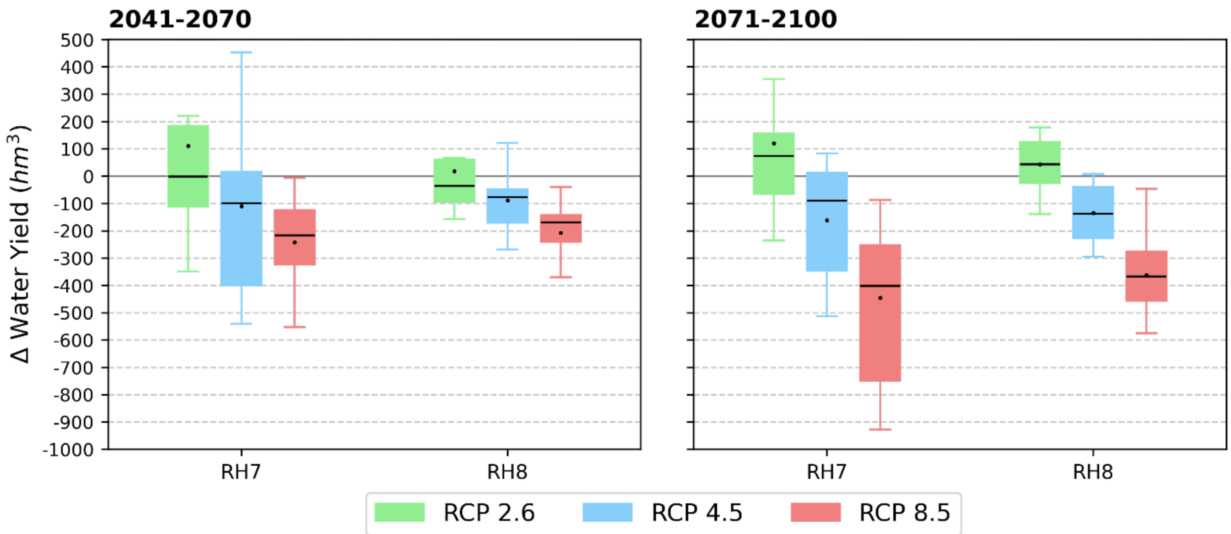


Figure 2.86 – Projected changes in averaged water yield (hm^3) for River Basins RH7 Guadiana and RH8 Ribeiras do Algarve. Two future periods are shown: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5 and RCP8.5. The black line represents the ensemble median.

Although the decrease in water yield may seem relatively small in RCP4.5, the impacts will be quite severe in absolute terms, since water availability and demands in the Algarve are already critical. If no adaptation measures are implemented to cope with this imbalance, it will become more severe throughout the century and will be responsible for the increase in water scarcity in the region. This is clearly represented through the analysis of the anomalies of the WEI+ for the River Basins that partially overlap with the NUTS II Algarve region (Figure 2.87). The index worsens across all scenarios and periods, even when water yield is expected to increase, as in the case of the RCP2.6 scenario. In fact, in this scenario, the increase in WEI+ is driven by the demand for water, stemming from modifications in crop water needs primarily due to a slight temperature rise.

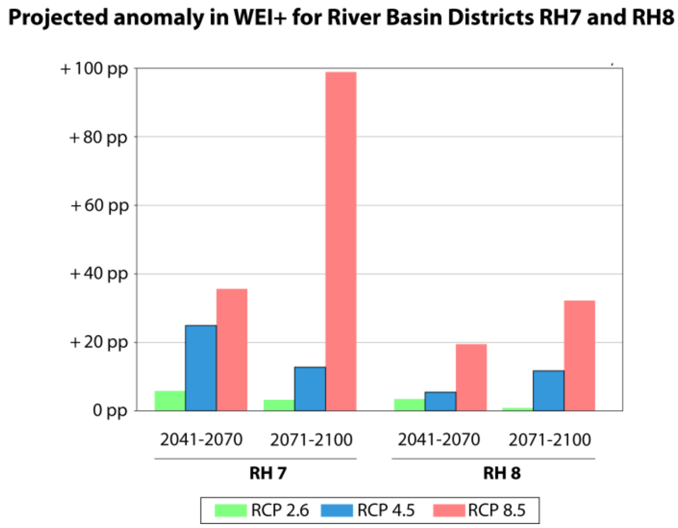


Figure 2.87 – Projected change in WEI+ (in percentage points) for River Basins RH7 and RH8. Two future periods are shown 2041-2070, and 2071-2100, under three emission scenarios – RCP2.6, RCP4.5, and RCP8.5. The presented values refer to the ensemble median.

Climate change can affect both irrigation requirements and productivity of the main crops grown in mainland Portugal. Table 2.52 illustrates these impacts on four crops: orange, corn, almond, and olive grove, representing 71.6%, 0.5%, 0.2%, and 0.1% of the crop's productivity considered in NUTS II Algarve. For olive groves and almonds, relative stability is observed across various climate change scenarios. Similarly, the projections for orange productivity also indicate relative stability, except for RCP8.5 at the end of the century, which shows a significant projected loss of -7%. However, a clear trend of decreasing productivity is noted for grain corn, which could lead to a production decrease of up to -9% in RCP4.5, compared to current productivity levels.

Considering all costs and benefits due to climate change in crops, the overall economic losses can amount to more than 3.2 million euros per year for the time frame 2041-2070 and more than 5.6 million euros for the period 2071-2100 in RCP4.5. Economic losses in productivity are related to modifications in climatic conditions for the crops currently developed in the region due to changes in plant phenology.

Table 2.52 – Projected changes in productivity in average % for orange, corn, almond, and olive grove in NUT II Algarve for two future periods: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5 and RCP8.5. The presented values refer to the ensemble median.

NUTS II Algarve	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Orange	0.4%	0.4%	-1.5%	0.2%	-0.5%	-7.1%
Corn	-6.1%	-6.1%	-8.6%	-4.0%	-9.4%	-14.4%
Almond	-0.1%	-0.3%	-0.4%	0.0%	-0.4%	-0.6%
Olive grove	0.0%	-0.4%	-0.8%	-0.2%	-0.4%	-1.0%

Apart from the need for a careful assessment for the construction of new reservoirs, with updated meteorological and hydrological information, considering compliance with the DNSH (Do No Significant Harm) principle and also, proof that it continues to be an option in climate change scenarios (climate-proof), ensuring resilience now and in the future, it is imperative, firstly, to make a strong commitment to efficiency measures. Action should therefore consider minimizing losses to insignificant levels, reducing natural water consumption, which can be replaced in part by alternative sources such as water for reuse, changing crops to crops more adapted to existing conditions, among others. Therefore, the exercise presented focuses on identifying measures that allow the effects of the increase in the scarcity index, which currently exists, to be nullified throughout the 21st century and for different climate scenarios, through solutions that essentially affect the demand side.

To adapt the Algarve to the projected impacts of climate change on water resources and agroforestry, it is proposed that the initial measures to be implemented be of the no-regrets type, notably promoting the reduction of losses in the distribution network in hydro-agricultural developments and to increase irrigation efficiency throughout the region.

Currently, the reality in the hydro-agricultural developments of the region varies significantly. For example, the hydro-agricultural development of Silves, Lagoa e Portimão, reports losses in the distribution network of around 30%, while the hydro-agricultural development of Sotavento Algarvio reports 9% of losses. This measure proposes that all irrigation perimeters achieve distribution network efficiency levels around 90%.

Regarding irrigation efficiency, much has been done in recent years, although there is still room for improvement. Therefore, it is assessed that all irrigation in applicable crops transition to using drip irrigation systems, where irrigation efficiency typically ranges between 90-95%. In Algarve, the use of this type of irrigation in all cistus related crops, would be particularly relevant.

Additionally, it is recommended to consider reducing water losses in the distribution network for urban purposes, which currently reports losses of around 21%. Despite significant investments already underway in this area, further efforts to minimise water losses can help alleviate the critical water availability and demands in the region.

Subsequently, changing current irrigated crops to others with lower irrigation needs (low-regrets measure), combined with techniques promoting increased soil water retention and the implementation of water retention landscapes (win-win measure), can contribute to a longer maintenance of the balance between current water demand and supply in this NUTS II. This set of measures is targeted at agricultural areas, although the same principles can and should be applied to urban green areas. The use of Wastewater

Treatment Plants (ApR) as an adaptation measure (no-regrets measure) is already being implemented, and this effort should be sustained. When all the previous measures fail to maintain the balance between water supply and demand, a desalination plan for water used in irrigation (lo-regrets measure), and not only for human consumption, should also be considered to address water shortage. is also crucial to ensure the success of the suggested adaptation actions by raising awareness and providing training to farmers. Farmers' training must encompass adaptive agricultural practices to help them cope with changing conditions, including implementing water management techniques, introducing drought-resistant crops, and adjusting planting and harvesting schedules. In this context, it is worth noting that the impacts of climate change will not only affect water availability but also agricultural productivity. Even if all plant water and nutrient needs are met, productivity losses will occur in scenarios with higher greenhouse gas emissions/concentrations throughout the century due to changes in plant phenology.

Adaptation in RH8 Ribeiras do Algarve[83]

In economic terms, the projected impacts of climate change on water availability for RH8 could result in losses averaging up to 628 thousand euros per year in RCP4.5 for the time frame 2041-2070 and 1,1 million euros for the period 2071-2100. Considering other scenarios, gains can vary on average up to 365 thousand euros (RCP2.6 period 2071-2100), while losses can be as high as 3 million euros on average per year (RCP8.5 period 2071-2100).

In this River Basin, a decrease in the average annual volume stored in the reservoirs is projected, with values between -10.1% and -10.7% in the RCP4.5 scenario (Table 2.53). This situation is even more severe in the RCP8.5 scenario, where the decrease could reach almost -40% by the end of the century. For the RCP2.6 scenario, a considerable decrease is projected for the period 2041-2070, with no significant changes expected by the end of the century.

Table 2.53 – Projected changes in average annual volume stored in reservoirs in % for RH8, considering two future periods (anomaly) 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. The presented values refer to the ensemble median.

River Basins (RH8)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Reservoirs Availability	-5.1%	-10.7%	-22.6%	+1.2%	-10.1%	-39.8%

[83] For the adaptation in RH7, please refer to the Adaptation storyline for NUTS II Alentejo.

With the implementation of the above-mentioned adaptation measures in the RH8 the identified economic impacts could be minimised in these River Basins, and some benefits would be achieved.

Table 2.54 shows the overall results for RH8 in the WEI+ with the implementation of each of the following adaptation measures: reducing system water loss and leakages, improving irrigation efficiency, selection of crops better suited to climate change projections, and wastewater recycling and reuse.

Table 2.54 – Projected change in WEI+ (in percentage points) for RH8 are shown considering two future periods: 2041-2070, and 2071-2100, under three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. The presented anomalies refer to the ensemble median and consider the following factors: no adaptation, the improvement of irrigation efficiency, the selection of crops better suited to climate change projections, and wastewater recycling and reuse.

River Basins (RH8)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Climate change impacts (no adaptation)	+3.27 pp	+5.51 pp	+19.53 pp	+0.69 pp	+11.75 pp	+32.27 pp
Reducing system water loss and leakages	+1.75 pp	+3.89 pp	+16.84 pp	-0.43 pp	+4.53 pp	+27.31 pp
Improving irrigation efficiency (entails reducing system water loss and leakages simultaneously)	+1.41 pp	+3.52 pp	+16.27 pp	-0.64 pp	+4.11 pp	+26.59 pp
Changing current irrigated crops (entails reducing system water loss and leakages simultaneously)	+1.41 pp	+3.51 pp	+16.32 pp	-0.63 pp	+4.14 pp	+26.65 pp
Wastewater for reuse (entails reducing system water loss and leakages simultaneously)	-3.06 pp	-0.51 pp	+5.14 pp	-3.58 pp	+0.24 pp	+17.96 pp

All the individually modelled measures bring some benefit to the region through a reduction in the anomalies projected for WEI+. The measure that brings the most benefits to the region, among the ones that were modelled, involves wastewater recycling and reuse in combination with reducing system water loss and leakages on hydro-agricultural developments. In this case the anomaly in WEI+ can be reduced by up to 15 percentage points at the end of the century. It is noteworthy that these combined measures can improve the situation in RH8 to the point of reducing the anomaly in WEI to negative values if we consider RCP2.6 all over the century or RCP4.5 at the beginning of the century. In other words, this means that these measures will improve the current situation even in scenarios of climate change. It should also be noted that this indicator provides an overview of the River Basin RH8 Ribeiras do Algarve, with localised gains that are not translated in this macro analysis.

Once not all proposed measures were modelled, the prioritisation of all adaptation measures for RH8 is presented in Figure 2.88. The figure outlines the timeline for the full implementation of each measure aimed at mitigating the projected impacts of climate change.

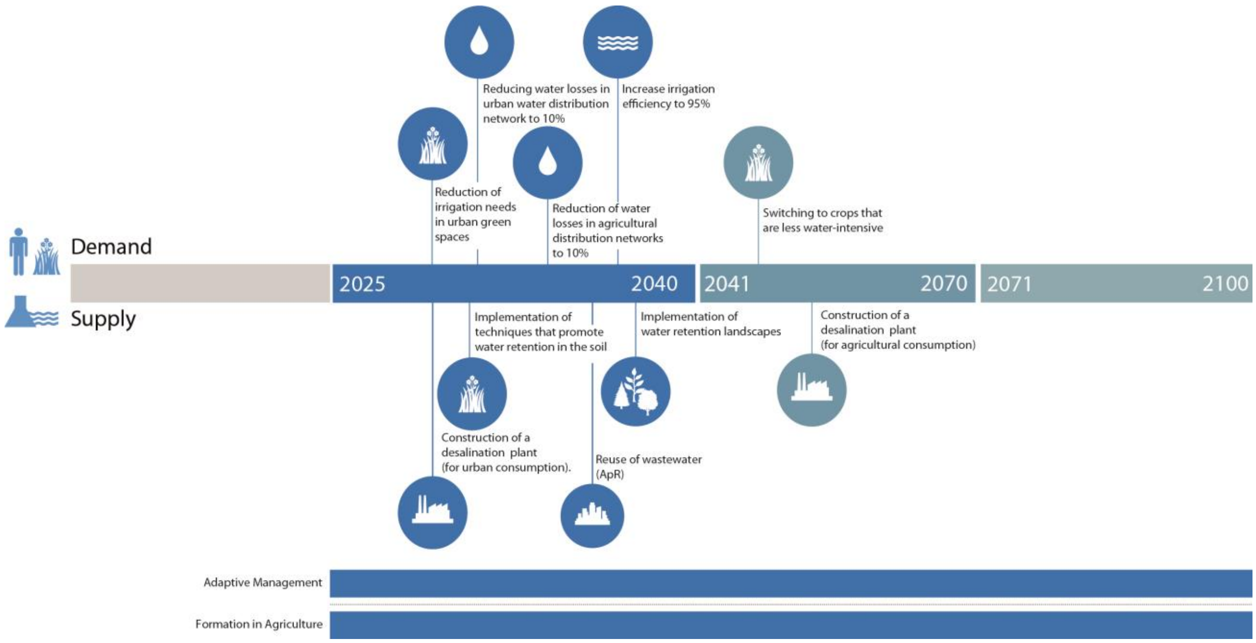


Figure 2.88 – Adaptation narrative for the water resources and agroforestry sectors in RH8 until 2100.

2.5.3. Coastal flooding

The Algarve region is a globally recognized touristic hotspot, mainly due to its long coastline, extending for over 230 km (Figure 2.89). While the westernmost half of the Algarve ("barlavento", in Portuguese) is generally characterized by rocky cliffs and pocketed beaches, the easternmost half ("sotavento") is dominated by long sandy beaches, most of them in a narrow dune strip between the Atlantic Ocean and the Ria Formosa coastal lagoon (of about 55 km long). Although diverse in its coastal environments, this region is shown to be particularly vulnerable to the impacts of rising sea levels and changes in wave climate patterns (the reader is referred to the WP4.5/6 dynamic modelling report). The different coastal environments comprise long sandy beaches (*e.g.*, from Tavira to Vila Real de Santo António), sandy beaches with adherent structures (*e.g.*, Quarteira), pocketed beaches and rocky cliffs (*e.g.*, Lagos region, and the coastlines of the "Costa Vicentina" Natural Park), a few urban beaches (*e.g.*, Lagos, Portimão, Armação de Pêra, Quarteira) and inland waters (*e.g.*, Ria Formosa, Guadiana River estuary).

Figure 2.89 – The Algarve NUTSII region, depicting the most relevant locations in terms of projected coastal vulnerability.

Overall, the vulnerability assessment carried for the Algarve region revealed highly vulnerable areas throughout most of the coastline, as soon as by the mid-21st century, and under a moderate concentrations scenario (RCP4.5). Most of the threatened areas were shown to be within the south-facing coastlines (especially along the estuaries and the Ria Formosa; Figure 2.90, for the intermediate RCP4.5 scenario). Note that the "barlavento" coastline is mostly rocky, with low physical susceptibility to the impacts of climate change. Nevertheless, several urbanized areas of the "barlavento" are projected to be highly vulnerable to changes in the total water levels[84], such as the cities of Lagos and Portimão, as well as in the village of Alvor. In central Algarve, along the Ria Formosa, moderate-to-high vulnerability can be expected across Praia de Faro, and Deserta, Farol, Culatra and Armona islands. Further inland, the lowest areas of the city of Faro (including the historical center), Olhão, Fuseta, Tavira and Conceição are also projected to be threatened, showing high vulnerability to flooding under extreme total water levels, associated to return periods as frequent as every 4 years. Along the "sotavento", the Guadiana River estuary shows moderate-to-high vulnerability in the majority of its extension, threatening almost half of the Vila Real de Santo António urban area. These results are consistent for all future periods (after 2041) and scenarios, despite small variations in the extension of the low, moderate and high vulnerability categories.

Considering the Algarve region as a whole, and for the three classes of vulnerability adopted (low, medium and high, associated to the 100-, 25- and 4-year total water level return values) projections revealed 6.5-

[84] The total water level (TWL) is given by the sum of the sea level rise (SLR), tide and storm surge components. For the ocean-facing coastlines, the run-up associated with a 99th percentile energy wave event is also considered.

12.5 km² of vulnerable ocean-facing coastlines (beaches), and 36.2-40.8 km² of vulnerable coastlines facing inland waters (mostly in the Ria Formosa and Guadiana River estuary; Table 2.55), depending on the future period and scenario. Departing from the intermediate RCP4.5 scenario, on a trajectory closer to the RCP8.5, an increase up to 3.4 km² in the vulnerable areas of Algarve is projected by 2100.

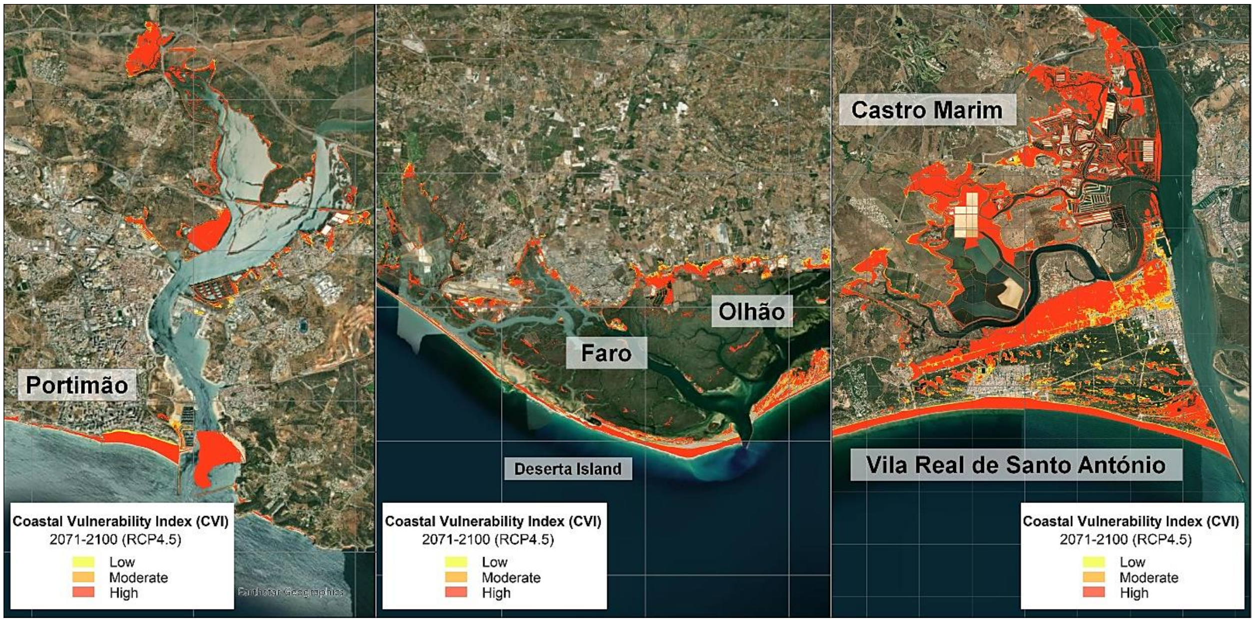


Figure 2.90 – Projected vulnerable areas along three coastal stretches of the Algarve region ("barlavento" - Portimão, Ria Formosa - Faro, Olhão, barrier islands, and "sotavento" - Vila Real de Santo António and Castro Marim), by the end of the 21st century (2071-2100), under the RCP4.5 scenario. The CVI is inversely related to the TWL 4-, 25- and 100-years return period values (*e.g.*, a high CVI is given to coastal areas projected to become flooded under a 4-year RP TWL).

Table 2.55 – Area (in km²) of the vulnerable coastal stretches in the Algarve region (grouped for the three classes of vulnerability), by the end of the 2041-2070 and 2071-2100 future periods, under both RCP4.5 and RCP8.5 scenarios.

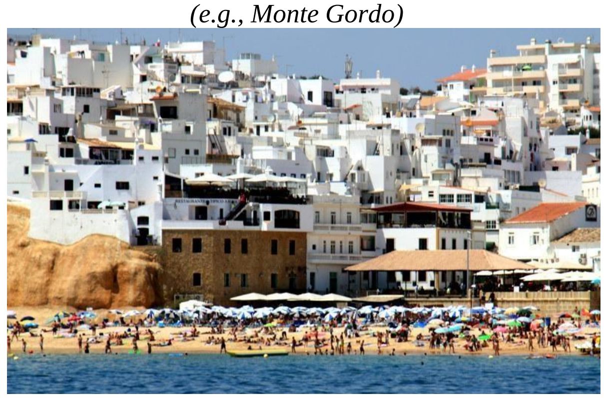
Vulnerable coastal areas (km²)				
Algarve region	2041-2070		2071-2100	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Ocean-facing	6.5	11.2	11.6	12.5
Inland	36.2	36.3	38.4	40.8
Total	42.7	47.5	49.9	53.3

Considering the diverse coastal typologies of the Algarve region (Figure 2.91), a single common adaptation narrative is not feasible. Instead, these have to be built for the multiple coastal environments. Therefore, Figure 2.95 depicts, schematically, the proposed adaptation pathways along the five identified coastal environments in Algarve. For each one, different pathways are shown, spanning from the present time until the end of the 21st century, and varying due to: (1) each coastal environment's expected response to changes in total water levels and wave characteristics (if facing the ocean), (2) the different possibilities in terms of adaptation strategies, and (3) any site-specific adaptation effort that was already carried in the recent past.

Sandy beaches with adherent structures
(e.g., Quarteira)

Low-lying sandy beaches
(e.g., Monte Gordo)

Pocket beaches and rocky cliffs
(e.g., Lagos – Praia do Camilo)



Urban beaches
(e.g., Albufeira – Praia dos Pescadores)

Inland waters
(e.g., Ria Formosa)

Figure 2.91 – Different coastal environments in the Algarve NUTSII region. Specific adaptation pathways are built for each environment in Figure 2.95.

Overall, in accordance to the current national-scale adaptation strategy (Pinto et al., 2020), artificial beach nourishment (Figure 2.93) corresponds to a transversal measure, to be applied consistently throughout most of the Algarve coastline, except along sandy beaches with increased sedimentary stocks and the coastlines facing inland waters. Note, nevertheless, that such interventions are usually quite localized and may vary greatly in terms of frequency and intensity even within the same coastal environment. Across the Algarve, artificial beach nourishment has been extensively used in the Lagos, Portimão, Lagoa and Silves beaches (*e.g.*, Praia Dona Ana, Alvor, Vau, Carvoeiro, Benagil, Cova Redonda, Quarteira, Vale do Lobo), however, these interventions are greatly dependent on the beaches' relevance for tourism, which dictates that other areas with similar coastal environments and vulnerability might not be eligible for this measure. Nevertheless, due to the large sedimentary availability in two borrow sites along the Algarve coastline, artificial nourishment is considered as the most viable adaptation measure for such a coastal typology, at least until the middle of the 21st century.

The accommodation of the adherent structures (*e.g.*, seawalls and tidal dykes; Figure 2.93) is shown as a functional option, essentially to protect the urbanized areas inland. Although it may be currently considered as a secondary measure, it is projected to become increasingly relevant towards the middle of the 21st century. Note, for example, that along the Quarteira's oceanfront, a sedimentary balance was achieved due the construction of groins, which contributes to reducing the local needs for artificial nourishment interventions (Figure 2.95). Nevertheless, extreme wave conditions in the context of sea level rise are projected to compromise the existing adherent structures that protect most of Quarteira's urbanized area. Due to long-term sea-level-rise-induced shoreline retreat, not only is artificial nourishment projected to become ineffective in several areas of the Algarve (given the permanent flooding of the pre-existing beaches in the base of the adherent structures), but the low-lying areas surrounding the inland waters of Ria Formosa are also projected to become increasingly threatened. The required topographic height (relative to the National Vertical Datum CASCAIS1938) for the coastal protection structures to withstand the future projected extreme coastal events[85] is set at 7.77 m, for the analysis conducted at Praia de Faro, under the intermediate RCP4.5 scenario (Figure 2.92). Excluding wave action, the required height for inland waters coastal protection structures is set at 2.99 m, in order to sustain a 100-year return period event by the end of the 21st century. Departing from the RCP4.5, on a trajectory closer to the RCP8.5, while an increase of up to 0.20 m (2.99 m → 3.19 m) is expected for the structures' heights facing inland waters, for the ocean-facing ones, the value is projected to be lowered by 0.28 m (7.77 m → 7.49 m). These values should be considered as references to all ocean-facing and inland waters coastlines of the Algarve region.

[85] Considering a 99th percentile wave energy event over a 25-year TWL return value.

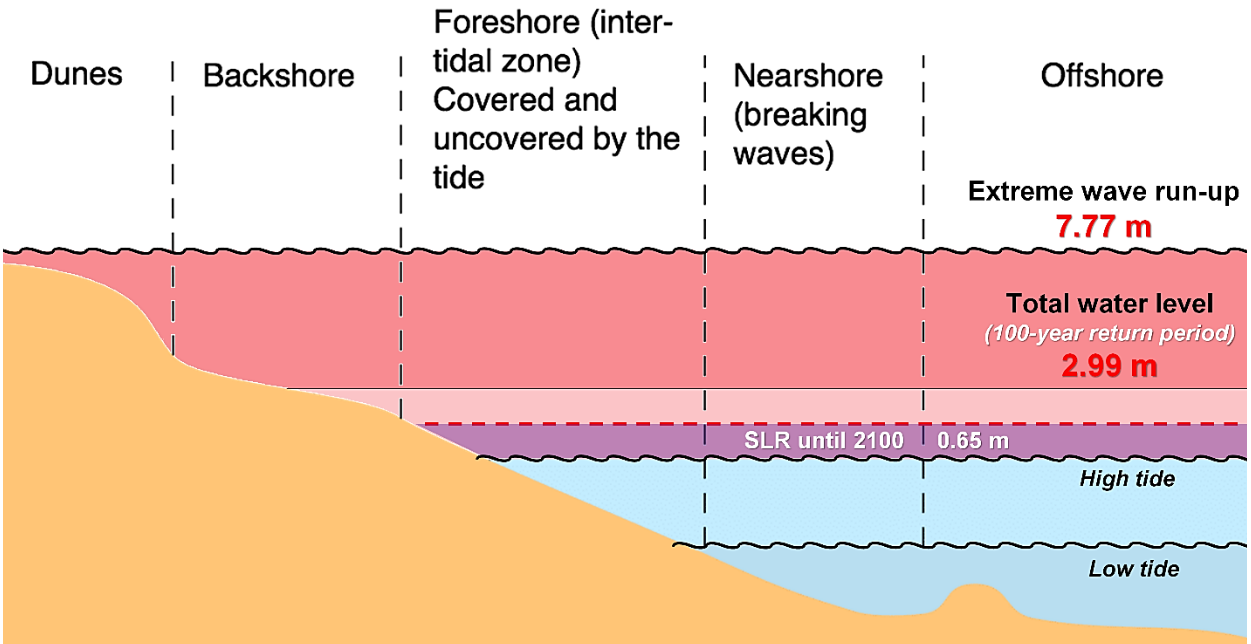


Figure 2.92 – Schematic depiction of how changes in total water levels and run-up may lead to coastal flooding. Note that while for inland waters the maximum coastal flooding topographic height is projected to be set at 2.99 m, for ocean-facing coastlines the value is projected to be set at 7.77 m (values for the RCP4.5 scenario by the end of the 21st century).

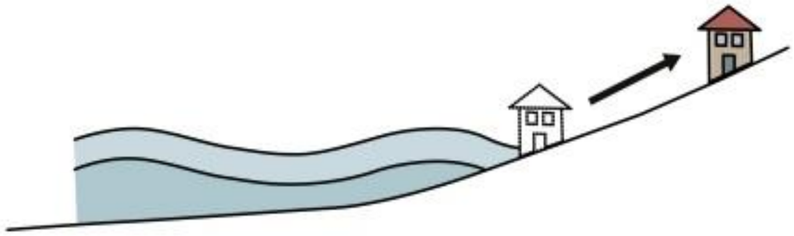
While accommodation may still be a viable option towards the end of the 21st century, planned relocation actions (Figure 2.93) should become the most cost-effective way to deal with continuously rising sea levels and extreme coastal flooding along most of the Algarve's coastal environments. At Quarteira, for example, even after the accommodation of the oceanfront adherent structures, the landward pressure of rising waters is projected to become too severe to be dealt with without considering relocation, as other areas surrounding the city become permanently flooded (Figure 2.95). Along the rocky cliffs and pocket beaches, however, the natural terrain configuration is enough to protect local populations from changes in the sea levels. Nevertheless, without continuous artificial nourishment interventions (which should be considered as a local option - and not a generalized one - if the economic or natural value of the beach justifies it), the pocketed beaches are projected to disappear or be extensively reduced towards the end of the 21st century.

Artificial nourishment

Accommodation of adherent structures

Cliff stabilization

Demolition of exposed illegal or non-essential structures



Planned relocation

Figure 2.93 – Examples of adaptation measures to be applied in the Algarve region, and present in the proposed adaptation pathways of Figure 2.95.

The demographic and cost-benefit analysis performed for the Algarve region is expressed in Table 2.56. Under the RCP4.5 scenario, more than 15000 habitants (according to the CENSOS2021) are projected to become vulnerable[86] until the end of the 21st century, from over 6600 vulnerable buildings. Total inaction costs related to patrimonial losses (without adaptation measures; TIC) top at over 4349 and 4957 million € by 2070 and 2100, respectively, for all coastlines (both inland and ocean-facing ones). The portion of the TIC associated to each coastal municipality of the Algarve region is depicted in Figure 2.94. Total adaptation costs (TAC), calculated exclusively for ocean-facing coastlines, are set at 457 and 708 million €, exceeding the TIC for the same coastlines (377 and 500 million €). Therefore, while fostering adaptation strategies is overall recommended for the Algarve region, the advantages of reducing local populations' exposure to coastal hazards are significant, and relocation efforts are suggested for the most urbanized ocean-facing coastal stretches (Figure 2.95), due to the unbalanced cost-benefit ratio of the remaining adaptation measures in these coastal environments. Furthermore, since most of the vulnerable areas are in fact located in the margins of the Ria Formosa, adaptation might require other potentially costly strategies, such as building additional dykes (which could help postponing the required relocation efforts), which were not considered in the analysis.

Table 2.56 – Demographic (number of vulnerable residents and buildings projected as vulnerable, *i.e.*, under CVI) and economic cost analysis considering the total inaction costs (TIC) and the total adaptation costs (TAC) in the Algarve region, by 2070 (end of the 2041-2070 period) and 2100 (end of the 2070-2100 period), under the RCP4.5 scenario.

Algarve region (RCP4.5 scenario)	2070	2100
Number of residents under CVI	13423	15009
Number of buildings under CVI	5929	6603
TIC from 2024 onwards – maximum (M€)	4349.3	4957.8
TIC from 2024 onwards – maximum for ocean-facing coastlines (M€)	377.4	499.8

[86] *i.e.*, exposed to at least a 100-year return period flooding event.

TAC from 2024 onwards for ocean-facing coastlines (M€)	457.2	708.7
Annualized maximum TIC (M€/year)	92.5	64.4
Annualized maximum TIC for ocean-facing coastlines (M€)	8.0	6.5
Annualized TAC for ocean-facing coastlines (M€/year)	9.7	9.2

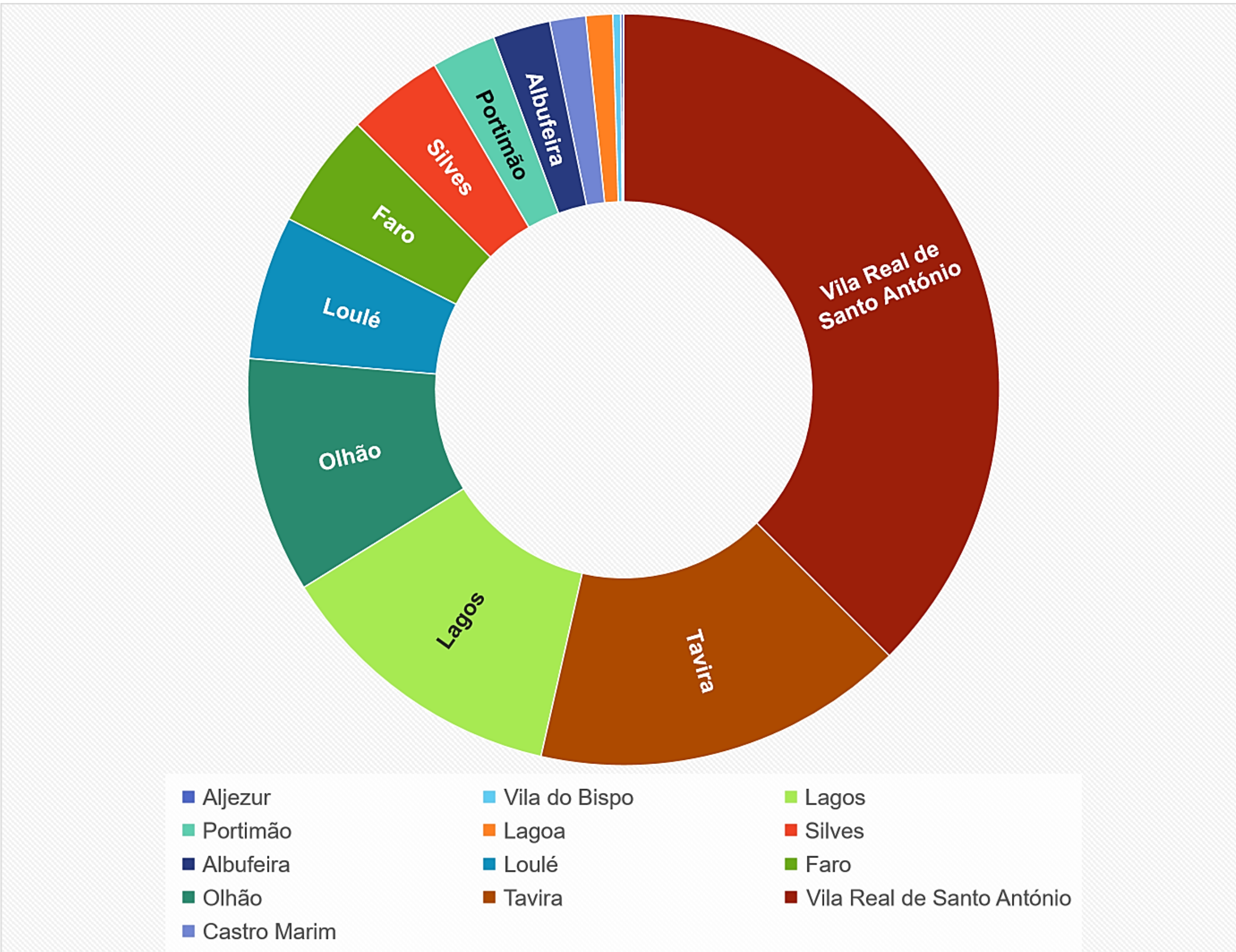


Figure 2.94 – Portion of the TIC (until 2100 under RCP4.5) associated to each coastal municipality of the Algarve region.

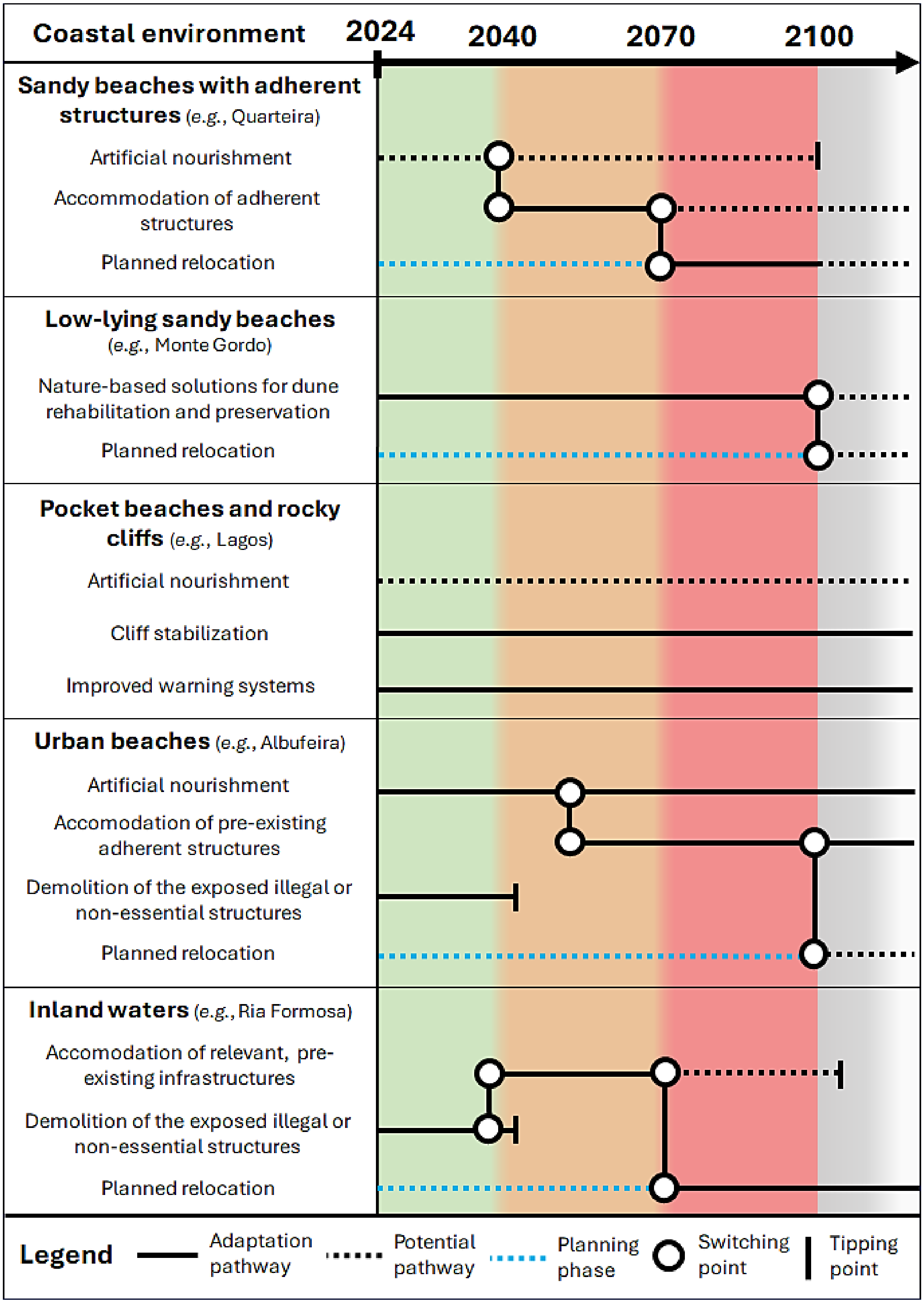


Figure 2.95 – Proposed adaptation pathways along the five identified environments present in the Algarve NUTSII region, departing from the year 2024, and spanning until the end of the 21st century. The pathways in full correspond to the most viable adaptation strategy for each coastal environment.

2.5.4. Forest fires

The climate of the Algarve region in Portugal is characterized by its Mediterranean climate, featuring hot, dry summers and mild, wet winters. With over 300 days of sunshine per year, the Algarve enjoys long and warm summers. The Algarve region boasts diverse vegetation, ranging from coastal dunes and salt marshes to inland forests and cultivated farmland. Along the coast, scrubland dominated by aromatic plants like lavender and rosemary may be found. Moving inland, cork oak and pine forests cover the landscape, providing habitats for diverse wildlife.

When it comes to forest fires, the Algarve is recognized for extensive burned areas (Figure 2.96), primarily concentrated in the Serra de Monchique region. From 2001 onward, Algarve has experienced four years where the extent of burned areas exceeded 20,000 ha (about 4% of the total area of Algarve): specifically in 2003, 2004, 2012, and 2018. Notably, these four years contributed to approximately 97% of the burned area over the last 22 years in the region. To understand the variable distribution and damage caused by wildfires and to devise practical adaptation options, it is crucial to consider several factors. Among these, meteorological conditions emerge as pivotal in influencing fire danger. Weather and climate, along with vegetation condition, composition, and human factors, play crucial roles in shaping fire regimes.

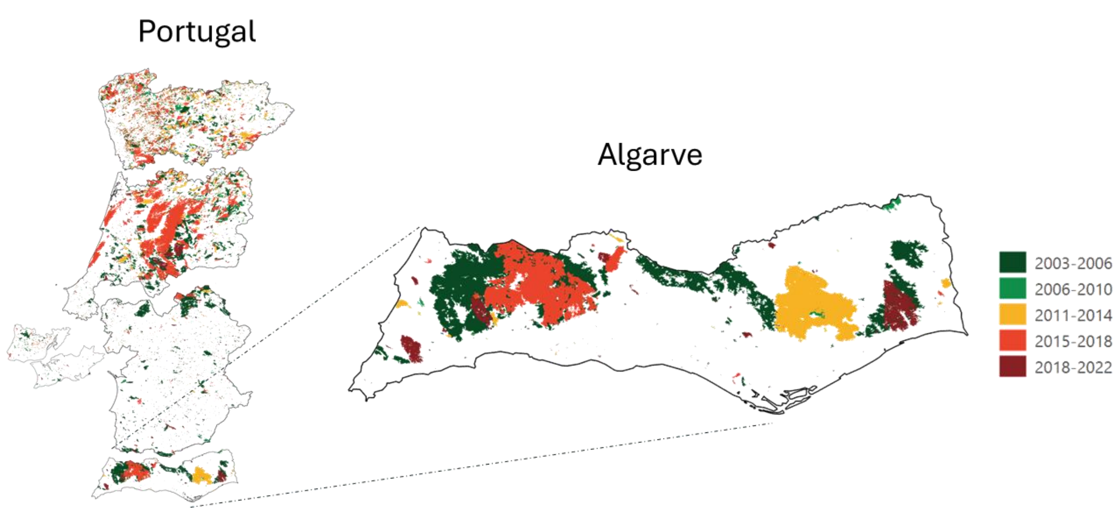


Figure 2.96 – Highlight of Algarve burned area, with the colours representing the period where the last occurrence took place.

Meteorology is key in defining the composition and structure of vegetation fuels but also holds a central position in determining the susceptibility of these fuels to fire. Human activities and vegetation management practices contribute to the present state of vegetation fuels, while their typology is intricately linked to the broader ecological domains they inhabit. Weather effects exert a profound influence on the vulnerability of vegetation fuels to ignition. They can control the moisture content of different fuels, enabling rapid wetting or drying of fine fuels such as litter, needles, mosses, and twigs. The response is comparatively slower for coarser wooden fuels. The moisture levels in these various fuels, coupled with meteorological factors like wind speed, collectively influence the ease of ignition, potential propagation, and severity of a fire. Recognizing the pivotal importance of meteorology in fire danger assessment is imperative for developing effective strategies for wildfire preparedness and adaptation. A comprehensive understanding of how meteorological conditions interact with other factors contributes significantly to the ability to predict and manage wildfires. Forest management practices, such as prescribed burning, fuel reduction treatments, and landscape-scale planning are essential for reducing fire risk and enhancing ecosystem resilience. Integrating these practices with other fields of expertise, such as ecology, hydrology, and land-use planning, can help optimize adaptation strategies and minimize trade-offs between conservation and fire management objectives. The Algarve region values its forests for the multitude of ecosystem services they provide, including carbon sequestration, biodiversity conservation, soil stabilization, and water regulation, contributing significantly to the region's environmental health and sustainability.

Meteorological forecasts and early warning systems are critical tools for mitigating fire risks and facilitating timely response efforts. Enhanced monitoring technologies, such as remote sensing, GIS mapping and decision support systems, provide valuable data and insights for fire management decision-making. However, implementing these strategies requires overcoming various challenges, including limited funding, conflicting land-use priorities, regulatory constraints, and social resistance. Addressing these barriers and fostering collaboration between government agencies, non-profit organizations, private landowners, and local communities is essential for effective wildfire management in the Algarve region.

Hence, the future meteorological danger was assessed by taking advantage of the enhanced Fire Weather Index (FWIe)[87]. It is projected a significant increase in the number of extreme fire danger days (Table 2.57), i.e., the number of days where FWIe is extremely high. For the RCP4.5 more 8 (10) days in extreme fire danger for the mid- (end-) century are projected with respect to the historical values; slighter changes for the RCP2.6 are projected, from additional + 5 to +3 days, and for the RCP8.5 the number of extreme fire danger can escalate more +20 at the end of the century, more than doubling the 15-days mark observed in the historical climate.

[87] The enhanced FWI is a meteorological fire danger index that combines an atmospheric instability parameter.

Table 2.57 – Additional number of days per extended summer (June to September) with extreme fire danger for different emission scenarios compared to the present climate.

Algarve	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Additional days (present climate = 15 days)	+5	+8	+11	+3	+10	+20

The 2018 Serra de Monchique wildfire affected 27,000 ha[88] (Figure 2.97) and resulted in estimated losses of 2.1 million euros (assets covered by insurance only)[89], which corresponds to about 78 euros/ha. This highlights the urgent concern about the potential doubling of days with extreme meteorological danger in the region. In the current climate context, assuming similar losses per ha, the cumulative financial toll of forest fires over the past 20 years stands at around 14.2 million euros, i.e., about 700,000 euros/year.

[88] Relatório do Observatório Técnico Independente: https://www.parlamento.pt

[89] There is not an estimation of the representativeness of these insured assets to compute an overall lost due to this wildfire. This estimate is taken from the "Associação Portuguesa de Seguradoras" and may be found on https://www.apseguradores.pt/. For the dashboard on insurance protection gap for catastrophes please see https://www.preventionweb.net/news/dashboard-insurance-protection-gap-catastrophes.

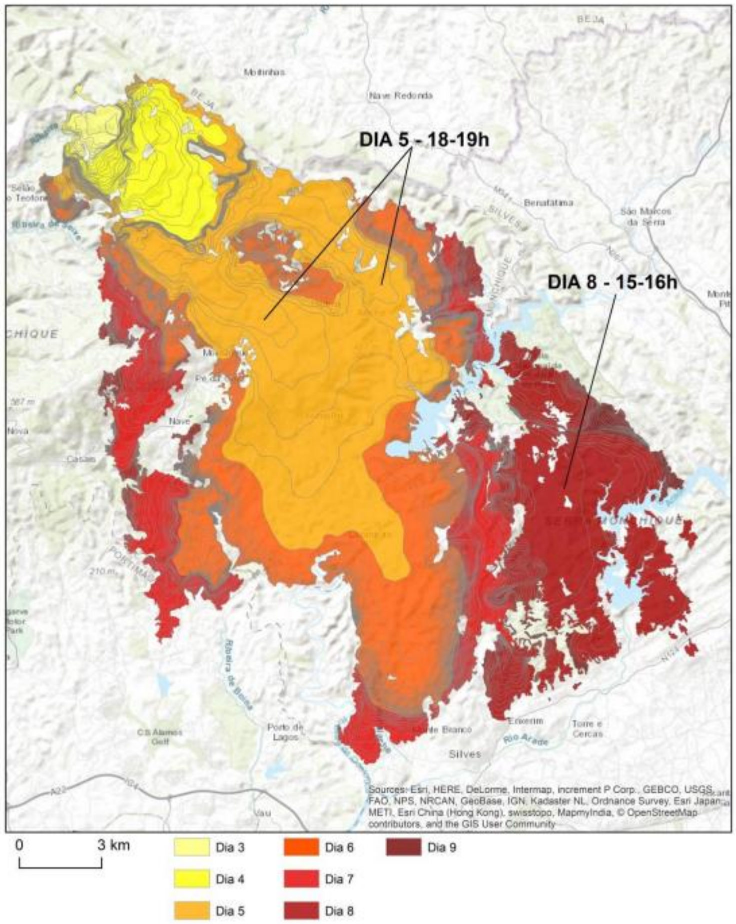


Figure 2.97 – Reconstruction of the 2018 Monchique wildfire by day (Source: Relatório Avaliação do Incêndio de Monchique from Observatório Técnico Independente, 2019).

The projections developed point to the doubling of the historical frequency of wildfires with fire radiative power as intensive as the 2018 Monchique event. Without proactive adaptation measures, the projected losses (Table 2.58) could escalate to nearly 1.3 million euros/year under RCP4.5 (almost doubling the 700,000 euros/year mark).

Table 2.58 – Projected losses without implementing adaptation measures, in million euros/year for Algarve (only considering ensured assets)[90].

Algarve (No adaptation)	2041-2070			2071-2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Losses (million euro/year)	1.31	1.35	1.45	1.04	1.35	1.84

[90] It is important to note that in Portugal the percentage of ensured assets is much less than those not ensured (https://www.preventionweb.net/news/dashboard-insurance-protection-gap-catastrophes).

In response to the escalating threat of forest fires exacerbated by climate change, it is paramount for the Algarve region the recognition of the critical importance of implementing adaptation strategies to safeguard its natural landscapes and communities. Drawing upon insights from diverse fields of expertise, including forest management and ecology.

Acknowledging the invaluable role of forest management practices in mitigating fire risk, efforts are underway to implement targeted interventions aimed at reducing fuel loads and enhancing ecosystem resilience. By leveraging knowledge of the region's diverse forest types, which range from cork oak forests to pine stands and Mediterranean scrublands, tailored management strategies can be developed to optimize fire prevention and suppression efforts. This includes prescribed burning, selective thinning and creating strategic firebreaks to interrupt the continuity of fuel and limit fire spread.

Following the objectives of *Roadmap for carbon neutrality 2050 (RNC2050)*, a paramount objective is to significantly decrease the annual burned area to a fraction of its current extent by 2050, marking a substantial reduction. This necessitates meticulous planning for the utilization of post-fire areas, prioritizing reforestation efforts with species resilient to fire and conducive to carbon sequestration, thus preventing deforestation and the conversion of forests into less productive land covers like scrubland. Additionally, adopting effective fire prevention measures, such as utilizing small ruminants to manage combustible materials, is crucial to mitigate fire risks and protect forest ecosystems. Enhancing forest management practices is fundamental to augmenting average productivity and resilience. Measures such as optimizing forest management techniques, intensifying fire prevention measures, and selecting more productive and climate-resilient species will lead to increased forest density and carbon sequestration capacity. By focusing on both production and protection species, the health and sustainability of forest ecosystems can be bolstered. Furthermore, accelerating afforestation efforts and curtailing the expansion of non-forest land uses, particularly urbanized areas, floodplains, and scrublands, are essential. By prioritizing afforestation and sustainable land use practices, the Algarve region can effectively mitigate climate change impacts, enhance ecosystem services, and foster a resilient and sustainable future for both nature and communities.

However, effective adaptation requires more than just forest management; it necessitates a holistic approach that integrates education and awareness initiatives to foster a culture of fire prevention and safety. By engaging individuals of all ages, from school children to adults, in educational programs and outreach campaigns, communities can become active participants in wildfire prevention efforts. Understanding the ecological importance of forests, the risks posed by irresponsible behaviours such as discarded cigarettes or poorly managed outdoor activities, and the importance of adhering to fire restrictions are essential components of building a resilient society in the face of escalating fire risks. In addition to proactive measures, a responsive approach is crucial for addressing immediate threats during periods of extreme meteorological danger. By leveraging advances in meteorological forecasting and early warning systems, authorities can anticipate and prepare for heightened fire risk on days with adverse weather conditions. This requires collaboration across disciplines, including meteorology, climatology, and data science, to develop robust predictive models that integrate real-time data on weather patterns, fuel moisture content, and vegetation stress indicators. The CEASEFIRE[91] platform is an example of such collaboration, with customised weather information for forest fire prevention, planning and fighting. By harnessing this knowledge and technology, decision-makers can make informed decisions about resource allocation, emergency response, and community evacuation, ultimately minimizing the impact of wildfires on lives, property, and ecosystems. While challenges remain in implementing these adaptation strategies, including technical complexities and resource constraints, the collective efforts of stakeholders from various fields of expertise underscore the urgency and importance of proactive climate adaptation in the Algarve region.

By integrating insights from forest management, ecology, meteorology and education, communities can build resilience to the growing threat of forest fires and ensure the long-term sustainability of their natural environment and way of life. These insights can be put in place under the three types of strategies that were assessed. One focused only on awareness measures, other on awareness and coercive measures, and the last only on coercive measures. Awareness measures cover initiatives such as continuous education and capacitation of the society. On the other hand, coercive measures encompass actions such as targeted fines. These adaptation measures aim to reduce ignitions and the costs related to large wildfires. For example, Figure 2.98 shows the projected losses without adaptation (black bar) and with implementation of adaptation measures (blue, green, and orange bars), in million euros/year for Algarve. Focusing on RCP4.5, the 700,000 euros/year mean values may reach 1.35 million euros/year under climate change, which means an increment of 635,000 euros/year.

[91] https://ceasefire.pt

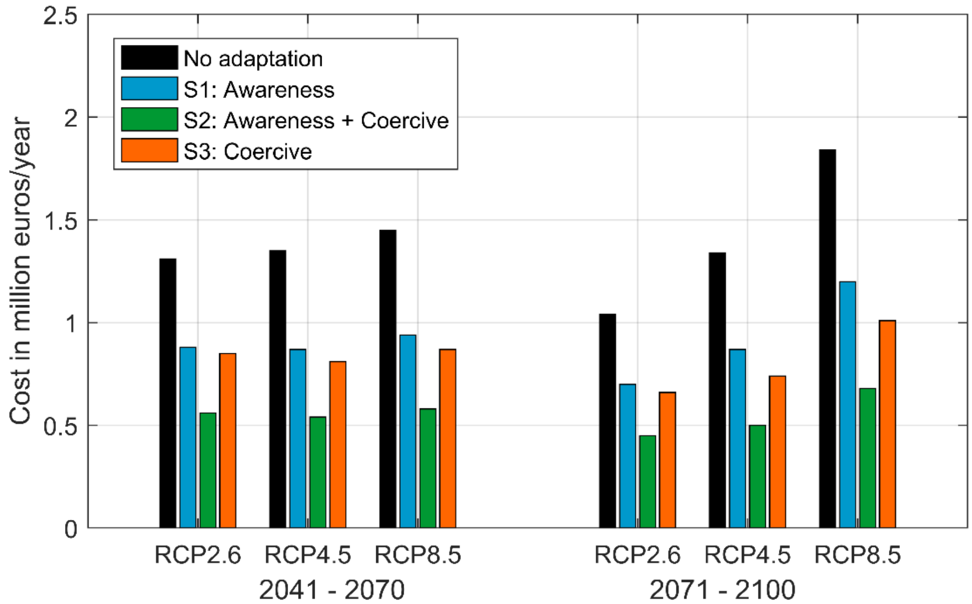


Figure 2.98 – Projected cost of no adaptation (black bar) and cost with implementation of adaptation strategies of Awareness (blue bars), Awareness + Coercive (green bars), and Coercive (orange bars), in million euros/year for Algarve, under RCP2.6, RCP4.5, and RCP8.5 for the middle of the century (2041 – 2070; left) and the end of the century (2071 – 2100; right).

With a strategy focused on awareness, it is possible to reduce the losses to about 875,000 euros/year. It is however important to note that with the advancement of time, climate change will severely impact the number of days in extreme danger, and consequently coercive strategies to reduce the number of ignitions and consequently burned area may be needed. These coercive-only strategies can represent savings of 425,000 euros/year. However, it is essential to note that a pathway focused on both awareness and coercive strategies brings better results, even decreasing the projected annual losses to about 500,000 euros/year, which represents savings of around 800,000 euros/year. Figure 2.99 shows the adaptation pathway for Algarve focused on RCP4.5. Several adaptation and mitigation strategies were already implemented and are expected to continue being implemented in the coming years. Awareness strategies should be first implemented to alert and educate society to the perils of climate change and its impact on forest fires. Eventually, in the most dangerous periods, coercive strategies should be implemented. However, with the increase in global warming, a mix between awareness and coercive continuous strategies must be implemented to prevent tragedies such as the 2018 Monchique fire to become the new normal.

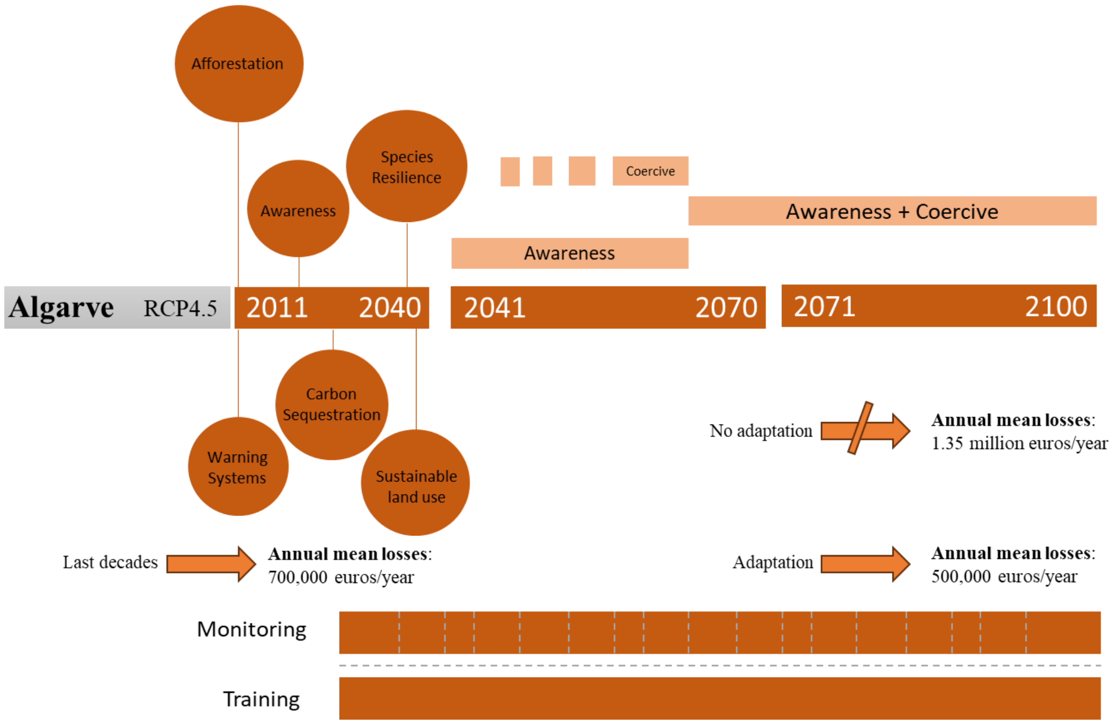


Figure 2.99 – Adaptation narrative for forest fires sector until 2100 for Algarve under RCP4.5.

3.Climate Risks for other Sectors

Energy

For the Portuguese energy system, the major threats come from extreme weather and climate events, such as heatwaves, droughts, water scarcity, extreme storminess and fires. Their occurrence, projected to be exacerbated in the future, will drive raise of energy demand for cooling, potential decreases in hydropower generation, reductions in the efficiency of thermal power plants, and risks to electricity distribution networks. The projected increases of drought frequency and heatwaves, and of their compound occurrence, might result in a growth of electricity deficit, affecting the availability of electricity during times of high demand (e.g. for cooling, irrigation, desalinization). Coastal and inland flooding, storms associated with extreme wind and precipitation, wildfires, and other climate-related hazards pose risks to Portugal's energy infrastructure, disrupting both production and transmission processes and leading to interruptions in supply. Additionally, decentralized energy production infrastructures, such as those under regimes like renewable energy communities and citizen communities for energy (CER, CCE), or others, which will experience likely relevant growth, inherently encounter heightened risks of exposure and vulnerability to the impacts of climate change. It's imperative to prioritize bolstering the resilience of these emerging production infrastructures."

Policies designed to foster Portugal's energy system transition to low-carbon alternatives must carefully consider the evolving climate conditions that the infrastructure will encounter over its lifespan. This means accounting for shifts in weather, especially extreme weather patterns, such as increased frequency and intensity of heatwaves and droughts, which could impact the performance and reliability of renewable energy sources like solar or hydroelectric power.

A dependable and affordable energy supply is essential for all sectors of Portuguese society. When disruptions occur in the energy supply chain, whether due to climate-related events or other factors, the consequences can surge across the economy, affecting industries, businesses, and ultimately the well-being of individuals. Thus, ensuring a stable energy supply is not just an economic necessity but also crucial for maintaining human health and quality of life.

Strengthening the resilience of Portugal's energy system involves a multifaceted approach. This includes integrating climate adaptation strategies into infrastructure planning to reduce the impacts of extreme events, prioritizing regular maintenance to minimize vulnerabilities and embracing technological innovations that improve efficiency and reliability. Measures such as enhancing energy efficiency, implementing demand-side management techniques to balance supply and demand, and deploying smart grid technologies can all contribute to strengthen energy security in the face of climate change challenges.

Social justice considerations must be central to Portugal's energy adaptation planning. This means ensuring equitable access to energy resources and services for all segments of society, particularly marginalized communities who may be disproportionately affected by energy-related challenges. This may become increasingly challenging in the context of stricter regulations and policies related to energy production and consumption (e.g., carbon pricing, renewable energy targets, and emissions reduction mandates). As energy companies may face compliance costs and investment requirements to adapt to these changes, their financial performance may be impacted, which could drive further increase in prices and promote energy poverty. Addressing issues such as energy poverty, where individuals or communities lack access to affordable and reliable energy, is essential for promoting social equity and inclusive sustainable development.

Human Health

The projections from the RNA2100 project reveal large increases in the occurrence of extreme temperatures, in particular in the frequency and duration of heatwaves, which are expected to result in increased heat stress among the population, and elevated rates of heat-related illnesses and mortality, especially in urban areas with poor air quality. These changes will pose a special threat for outdoor workers, such as in the agricultural and construction sectors, which will face amplified risks of heat-related illnesses, and injuries associated to wind and precipitation extremes. Additionally, the warming projections and changes in the precipitation patterns may create more favourable conditions for disease vectors, increasing the risk of disease spread. In fact, alteration in the geographic distribution and transmission patterns of infectious diseases, such as vector-borne diseases like Lyme disease and West Nile virus might be expected. Furthermore, changes in the (or even loss of) livelihoods and disruption of social support networks can contribute to stress, anxiety, depression, and other mental health disorders. As agricultural productivity and food availability can also be affected, increases in the risk of malnutrition and nutrient deficiencies may be expected, especially among the most vulnerable populations. In addition to these amplified risks, weather and climate extremes might strain healthcare systems, leading to increased demand for medical services, hospitalizations, and emergency responses during those events, like heatwaves.

The magnitude of the climate-related health impacts is dependent of various factors, including the quality of housing, availability and affordability of house-cooling apparatus, urban planning and design, and labour regulations governing working conditions. Addressing these broader determinants is essential for effectively mitigating climate-related health impacts. In fact, the vulnerability to climate-related health risks is often larger among socially disadvantaged groups, including low-income population, the elderly, children, and individuals with pre-existing morbidity. Factors such as limited access to healthcare, inadequate housing, and occupational exposures exacerbate the health impacts of climate change for these population groups. It is therefore crucial to integrate human health considerations into all climate change adaptation policies and strategies to effectively mitigate and manage climate-related health risks. Enhancing the capacity and preparedness of the health sector is essential for responding to climate-related health emergencies and providing adequate healthcare services to affected populations. Preparedness and response capacity should rely in adequate early warning systems for weather extremes. Critical health infrastructure, including hospitals, clinics, and emergency response systems, must be made more resilient to climate impacts to ensure continuity of healthcare services during extreme weather events and other climate-related emergencies. Adaptation measures should be designed to address disparities in vulnerability and ensure equitable access to healthcare services and resources for all population groups, particularly those most at risk from climate-related health impacts.

Tourism

The tourism sector is rather vulnerable to the projected changes found in the context of the RNA2100 project. The future expected maximum and minimum temperature changes depict a mean climate much warmer than presently. Moreover, more frequent and severe heatwaves are projected, which might negatively impact tourism by diminishing attractiveness to tourists, reducing visitor comfort levels and deterring outdoor activities, such as beachgoing, sightseeing, and hiking during peak tourist seasons. Tourism is a major employer in Portugal, providing jobs directly and indirectly to a significant portion of the population. According to the Portuguese Ministry of Economy, the tourism sector was the origin of 19.1% of the wealth produced in 2023 in Portugal. As presently in Algarve, water scarcity poses real threats to tourism development due to the emergent water use conflicts. The projected precipitation decreases, especially for the South of Portugal, and augments in the frequency and severity of droughts might disturb tourism infrastructure and services, including golf courses, swimming pools, and irrigation systems for parks and gardens. Additionally, drought conditions will impact severely natural ecosystems and agricultural/forest landscapes, diminishing their appeal to tourists.

Rather importantly, the large escalations in the number of days of extreme meteorological fire danger projected, and the increase of precipitation extremes, might disrupt travel plans, cause damage to infrastructure, and pose risks to the safety of tourists. For example, wildfires in forested areas can lead to evacuation orders and closures of hiking trails or natural parks, impacting nature-based tourism activities; as well as flash floods inland near river streams. Most of the touristic offer in Portugal seats in coastal areas, whereby the projections of coastal erosion and flooding found in the RNA2100 constitute an increasing risk for the tourism sector. Both future long-term coastal erosion and short-scale extreme coastal flooding events will lead to loss of beaches, damage to coastal infrastructure, and increased flood risk for coastal communities and tourist destinations. Permanent inundation due to sea level rise may also affect the viability of coastal resorts and businesses, as well as the safety of tourists visiting coastal areas.

Finally, the attractiveness of Portugal to visitors may also be reduced due to the impacts of climate change on the natural and cultural heritage, including biodiversity hotspots, historic towns, monuments, and archaeological sites. The projected rising temperatures, changes in temperature extremes and precipitation patterns, and extreme weather events might accelerate the degradation of ecosystems and cultural assets, diminishing their attractiveness to tourists and compromising their long-term preservation.

Cities and Urban Planning

The RNA2100 climate change results imply significant challenges to cities in Portugal, exacerbating existing vulnerabilities and requiring robust adaptation measures. Portuguese cities face multidimensional challenges due to regional climate change, including amplified heat stress, increased frequency of extreme weather events, water scarcity, and coastal flooding risks. Overall, all cities in Portugal are projected to experience intensified heatwaves and an increasing frequency and duration of droughts. The temperature extremes are expected to be specially challenging in urban areas with limited green and blue infrastructures, solar shading, and air conditioning installations, as is the case of most of the Portuguese cities. In major urban areas, such as the metropolitan areas of Lisbon and Porto, and medium size cities and Braga and Coimbra, the rising temperatures amplified by the local urban heat island effect will particularly affect vulnerable populations, such as the elderly and socioeconomically disadvantaged communities, disproportionately impacted due to limited access to cooling amenities and healthcare services. The urban heat island effect is a paramount concern to consider when planning the urban space as it can add a few degrees to a specific site on top of the regional temperature. In the southern Portuguese cities, the large projected decreases in rainfall will greatly exacerbate water scarcity issues. In fact, the competition for water is already growing in these cities, between domestic uses and all other needs, such as agriculture irrigation demand and the tourism sector, a problem which is foreseen to become larger and larger in the near future. In the northern Portuguese cities, on the other hand, projections indicate enhanced extreme precipitation events, leading to increasing pluvial flooding risks including flash floods. Flooding risk extends to most of the coastal cities, which will face escalating challenges from sea-level rise and compound flooding events, threatening critical infrastructure and livelihoods. Coastal metropolitan areas and cities such as Viana do Castelo, Esposende, Vila do Conde, Porto, Aveiro, Lisbon, Setúbal, Faro and Vila Real de Santo António are projected to experience more frequent extreme coastal flooding events, which may become particularly challenging in areas without natural protection features (such as dunes and vegetation) as well as in densely urbanized stretches in the vicinity of estuarine areas, where sea level rise will progressively result in permanent inundation.

All these threats requite clear and strategic adaptation measures tailored for the diversity of Portuguese cities, although some should conceptually be envisaged for most of the urban areas. The implementation of green infrastructures is crucial, which corresponds to prioritizing the integration of large green spaces and blue corridors within urban planning, to effectively mitigate heat island effects and enhance biodiversity; based on real modelling efforts cities should foster the increasing of urban tree cover and develop green-blue networks to improve thermal comfort and also resilience to flooding. In what concerns to water management and the reduction of fluvial flooding risk, a new paradigm of city-scale water management must be pursued. The implementation of water-efficient practices and infrastructure upgrades to address competing water demands, promoting sustainable water use in urban areas through greywater recycling, stormwater harvesting, and aquifer recharge initiatives. Moreover, enhancing flood monitoring and early warning systems to mitigate risks to infrastructure and communities, investing in resilient drainage systems, green and blue infrastructure, and nature-based solutions to manage stormwater and reduce flood vulnerability. At an urban design scale, the promotion of climate-resilient urban landscapes is key, which may include to foster compact, mixed-use developments with sustainable building designs to minimize heat exposure and energy consumption, to scale-up climate-responsive architecture, such as cool roofs, green roofs, and passive cooling techniques, to improve indoor thermal comfort. For coastal cities, the enhancement of natural protection features through dune preservation and restoration, as well as the implementation of natural vegetation, is essential to protect urbanized areas from ocean storms. Accommodation of pre-existing structures, or even relocation, is also recommended, especially in the vicinity of inland waters, where inundation caused by sea level rise will be permanent.

The required adaptation needs for cities in the context of climate change relies in a great extent on community engagement and capacity building. Therefore, fostering stakeholder collaboration and community engagement in adaptation planning and implementation is vital, as well as empowering local authorities, civil society organizations, and residents through climate literacy programs, participatory decision-making processes, and capacity-building initiatives. The Portuguese cities contain rather large social asymmetries, which importantly demand an inclusive adaptation planning, to address social inequalities and vulnerable groups' needs in adaptation strategies. This will ensure equitable access to green spaces, healthcare services, and cooling shelters to safeguard public health and well-being during extreme weather events, in particular in heatwaves.

At the governance level, cities in Portugal might greatly benefit of integrated governance and financing, such as the adapt.local - Network of Municipalities for Local Adaptation to Climate Change created in December 2016, as a result of the ClimAdaPT.Local project. Strengthen institutional coordination and multi-level governance frameworks to facilitate adaptive decision-making and resource allocation; and, to mobilize EU funding, public-private partnerships, and innovative financing mechanisms to support climate resilience projects at the local level.

Finally, of paramount relevance are the knowledge sharing and learning networks. To promote knowledge interchange and collaboration among cities, research institutions, and international organizations to promote best practices and lessons learned in climate adaptation. Participation in EU initiatives, such as the Covenant of Mayors and EU Missions, is recommended, to access technical assistance and funding opportunities for climate resilience projects.

Cultural and Natural Heritage

Portugal is renowned for its rich and varied cultural and natural heritage, from historic landmarks to pristine ecosystems. Nonetheless, climate change poses a significant threat to these invaluable assets, jeopardizing their integrity and sustainability. The RNA2100 projections of increase in the number of days with extreme temperatures, and frequency and duration of heatwaves, may severely impact on cultural heritage, through exacerbation of degradation processes, such as salt crystallization and thermal stress, enhanced thermoclasty processes, affecting stone structures, frescoes, and artwork. Interior spaces, including museums and archives, will be increasing vulnerable to temperature fluctuations, leading to deterioration of collections and artifacts. Additionally, the projections of extreme precipitation and wind, associated with intense storms, and the dramatic increase in extreme meteorological fire risk days, pose direct threats to cultural heritage sites, from fluvial flooding to fires. All these combined might accelerate erosion processes, landslides, and structural damage which can compromise the integrity of historic buildings, churches, and cultural landscapes. Finally, coastal total water level projections are associated to extensive land areas highly vulnerable to coastal flooding and erosion, which constitute an increasing threat to coastal heritage sites, including historic towns and archaeological sites. Permanent inundation resulting from sea level rise may also result in the loss of ecosystems in low-lying areas, such as in estuaries and coastal lagoons (e.g., Ria Formosa, Ria de Aveiro). Furthermore, exposed to increasing coastal flooding and thus saltwater intrusion, buildings, monuments, and artifacts are at higher risk of deterioration and loss. Driven by all these factors the economic sustainability of cultural heritage will be in higher peril, once the climate-induced damages will diminish their attractiveness to tourists, resulting in potential income reduction for its management and local economies; moreover, the climate extremes and climate-induced damages might cause a declining in visitor numbers and revenue streams exacerbating socio-economic challenges for cultural heritage management and to the communities reliant on tourism.

The climate change impacts on the natural heritage sites of Portugal are mainly linked to the same climatic drivers. The projected warming and the changes in precipitation patterns, mainly reductions of rainfall, will drive more frequent and severe droughts, which coupled with habitat fragmentation, will increasingly threaten native flora and fauna species, leading to biodiversity loss. These losses will be faced by all the Portugal's diverse ecosystems, including forests, wetlands, and coastal habitats. The combination of more frequent droughts and intense extreme precipitation will compromise the resilience of natural heritage sites to soil erosion and degradation, water scarcity, and invasive species proliferation which further degrade ecosystem health and functioning. Most of the Portuguese protected areas are linked to coastal ecosystems, mountain ranges and river valleys, and estuarine areas, which are all especially vulnerable to the projected changes on the hydrological cycles, with less accumulated precipitation and more extreme precipitation, wildfires, and to coastal flooding onshore and on inland estuarine regions, which might compromise irreversibly these landscapes undermining their cultural significance and intrinsic beauty.

The cultural and natural heritage topics are very often disregarded in climate change vulnerability, impact, and adaptation analysis, which requires a fasten strategy to overcome this problem. A suitable design of adaptation measures for heritage demands a systematic effort focused on comprehensive risk assessments to identify vulnerabilities and prioritize adaptation actions for cultural and natural heritage sites and establishing monitoring systems to track environmental changes and assess the effectiveness of adaptation measures over time. Furthermore, the implementation of proactive conservation and restoration measures for cultural and natural heritage is crucial. In the framework of the EU biodiversity strategy for 2030, it is aimed an increase of the protected area to at least 30% of EU land and 30% of surrounding seas by 2030. Integrating real concepts of sustainability in natural sites management is of paramount relevance, adopting sustainable land and resource management practices to conserve natural heritage sites, promoting biodiversity conservation, restoring degraded ecosystems, establishing new protected corridor areas, and implementing habitat restoration projects to enhance ecosystem resilience and adaptive capacity. Regarding cultural heritage, to strengthen building codes, retrofit historic structures, and employ innovative materials and techniques to enhance resilience against extreme weather events and sea-level rise are pivotal.

As for most of of climate change adaptation with a territorial wide level, its efficiency is largely dependent of suitable community engagement and capacity building. In this way, it is highly advisable to promote community participation and stakeholder engagement in adaptation planning and implementation processes, to empower local communities, and heritage stakeholders through education, training, and outreach initiatives to enhance their resilience and governance of cultural and natural heritage assets.

Finally, it is crucial to integrate climate adaptation considerations into heritage conservation policies, planning frameworks, and funding mechanisms, to mobilize financial resources, including EU funds and public-private partnerships, to support adaptation projects and initiatives for heritage preservation and sustainability.

4.Final Remarks

Adaptation Narratives

Warming and drying future conditions may significantly affect human and natural environment in Portugal. The climate projections are found to be especially dramatic for the non-mitigated emission scenario (RCP8.5), while more manageable for the highly mitigated scenario (RCP2.6). The results here revealed very distinct change magnitudes and patterns within the three RCPs, which will lead to substantially different socio-economic impacts and adaptation needs. Even under a strong mitigation scenario, substantial changes for sectoral climate indices are projected, which may strongly impact sectors like agriculture and water management.

Water resources and agroforestry in mainland Portugal are vulnerable to climate change. Projected changes in precipitation, temperature, humidity, solar radiation, and wind will affect water availability, demand, and crop productivity. By the century's end, impacts will vary depending on emissions trajectory. Southern regions, particularly beyond the Tagus River, will face more significant impacts, with the Water Exploitation Index plus (WEI+) potentially increasing by up to +99 percentage points in the Guadiana River Basin under RCP8.5, or around +22 points under RCP4.5. Without adaptation, economic losses could average €426 million annually under the moderate mitigation scenario and approach €670 million under the high emissions scenario. Even meeting Paris Agreement targets could still result in yearly losses of €172 million by 2100. As climate change worsens, adaptation becomes crucial, especially in the south, where the gap between water supply and demand will widen. In northern regions, solutions like reducing demand and enhancing irrigation efficiency can help, while southern areas will require more profound adaptation, such as selecting climate-resilient crops and investing in desalination for agricultural purposes.

The discourse on climate adaptation and wildfire management in the five NUTS II regions elucidates the imperative for multifaceted strategies in confronting the escalating threat of wildfires exacerbated by climate change. The results emphasize the pivotal role of meteorological factors, forest management practices, and societal engagement in shaping wildfire risk and resilience. It underscores the necessity of integrating awareness initiatives with coercive measures to effectively reduce ignitions and mitigate projected losses (saving from 290,000 euros/year in A.M.L. to 88 million euros/year in Centro). Moreover, the delineated adaptation pathways underscore the importance of a nuanced approach that evolves with changing climatic conditions, emphasizing the significance of continuous adaptation efforts to prevent catastrophic events (such as the 2013 Picões fire in Norte, the 2022 Serra da Estrela fire in Centro, the 2022 Palmela fire in A.M.L., the 2023 Odemira fire in Alentejo, or the 2018 Monchique fire in Algarve) from becoming the new norm. Ultimately, by fostering collaboration across disciplines and implementing proactive measures, the Algarve region can aspire towards a resilient and sustainable future, safeguarding its natural environment and communities against the ravages of wildfires in a changing climate landscape.

The Portuguese coastal areas were shown to be extensively vulnerable to the impacts of climate change, arising from sea level rise and changes in the combination of tides, storm surges and waves. By the end of the 21st century, projections reveal up to 587 km2 (RCP4.5) and 604 km2 (RCP8.5) of vulnerable coastlines, for both the ocean-facing (9.3%) and inland waters' (90.7%) environments. Adaptation is overall recommended at national scale, despite the different results yielded by the cost-benefit analysis, depending on the region. Total inaction costs (without adaptation) are projected to surpass 12000 million € (RCP4.5) and 14000 million € (RCP8.5) until 2100, in contrast with approximately 5000 million € (for both scenarios) of expected adaptation costs. While indirect contributions from economic activities, tourism, ecosystem services and non-structural adaptation measures were not considered in the estimated economic costs, they provide a baseline to highlight the potential losses related to inaction (or maladaptation), as well as the benefits of adapting the Portuguese coastlines to future climate change.

Role of spatial planning in adapting to climate change (Direção-Geral do Território)

Spatial planning plays a central role in climate change adaptation. For this reason, not only have climate change issues become increasingly important in the analyses and proposals of territorial programmes and plans, but also regional and local adaptation strategies and plans attach great importance to spatial planning instruments as a means of promoting adaptation. This reality is particularly evident in the various documents produced with the aim of mainstreaming the climate change component into land-use plans at the municipal level, in the Municipal Master Plans (Planos Diretores Municipais, PDM), as well as in the methodological guides for the preparation of local adaptation instruments to climate change in Portugal. On the other hand, the achievement of adaptation to climate change depends, among other factors, on the forms of land use and occupation, i.e. the arrangement and organisation of human, natural and technological resources in the territory. This is a key aspect since it is in this context that the options that determine the capacity of the territory and society to adapt to the effects of climate change are framed.

Spatial planning has a particular role to play in increasing resilience to extreme climate events by identifying areas that are particularly vulnerable to events such as floods, coastal storm surges, heat waves or forest fires, and by enabling strategic planning of land use and infrastructure development to mitigate impacts and increase the resilience of communities and ecosystems. In this context, spatial planning instruments can be used to address the specificities of each territory by proposing measures, rules and interventions that are adapted to each reality, and are an effective means of promoting adaptation to climate change.

At the coastal level, given the sea level rise, extreme events, and the increase in coastal erosion due to climate change, the Coastal Programmes of Mainland Portugal promote the implementation of sustainable coastal defence strategies, the early relocation of vulnerable assets and the protection of natural habitats. Similarly, the Municipal Master Plans and the National Ecological Reserve, in coordination with the Flood Risk Management Plans, are highly effective instruments for flood risk management, as they not only avoid the occupation of flood-prone areas, but also anticipate the creation of flood areas, wetlands and green areas to assist on the management of excess water caused by heavy rainfall events, or limit the extent of soil sealing, particularly in critical river basins.

To ensure that biodiversity can adapt to climate change, the Special Protected Areas Programmes identify and protect biodiversity hotspots and protect corridors that facilitate species migration as temperatures rise. In order to promote the adaptation and resilience of human and natural systems to climate change, the Landscape Restoration and Management Programmes aim to contribute to the development of a more resilient and biologically and ecologically valuable landscape through the planning, programming and transformation of landscapes identified as vulnerable forest areas.

- In this sense, an approach that integrates adaptation to climate change with land use and urban planning policies will make it possible to:
- identify and take into account the specificities of each territory, placing them in the context of climate change dynamics;
- avoid land uses and occupations that could be problematic in the context of climate change, promote more sustainable use of the territory and its adaptive capacity, and take advantage of potential opportunities that may be identified;
- consider and integrate climate change mitigation and adaptation components, promoting synergies and complementarities;
- respond to the needs and expectations of territorial actors at different scales through the integration of consultation, involvement and participation mechanisms.

This interdependence between policies is fundamental to ensure climate resilience because adaptation is a territorial response adjusted to the local climate but also to the ecological and social characteristics of a territory and its vulnerability. An approach that recognises diversity and takes into account local characteristics is essential for good adaptation.

Integrating adaptation into Municipal Master Plans (Direção-Geral do Território)

Aiming to contribute to the promotion and integration of adaptation to climate change in planning and land use, and to build better responses to the projected climate impacts, the RNA2100 carried out a review of the current panorama of adaptation to climate change in spatial planning plans and programmes, and developed methodologies and criteria for integrating vulnerability to climate change and future impacts into spatial planning. The work was carried out in two phases.

In the first phase, the relationship between climate change adaptation and land use planning was contextualised in terms of policies and instruments, and the experience of implementing adaptation in land use planning instruments, namely the Municipal Master Plans (PDM), was assessed. This was done by identifying and analysing the adaptation measures included in local climate change adaptation plans and strategies, as well as those included in PDM. Practices for integrating adaptation into PDM were also assessed through a survey of municipalities (the local authorities responsible for preparing local plans) and interviews with the Regional Coordination and Development Commissions (the bodies that oversee the preparation of local plans) and a group of spatial planning experts who advise municipalities on their role.

Among the conclusions, it is worth highlighting the importance given by the municipalities to the major documents on spatial planning policy (National Spatial Planning Policy Programme) and climate change adaptation (National Strategy for Adaptation to Climate Change 2020), the existence of climate change adaptation instruments, and the recognition that spatial planning plays a very important role in the implementation of adaptation through its instruments, especially municipal master plans.

The contribution of climate adaptation planning instruments was more limited, as most municipalities did not take their existence into account when preparing their PDM. It was also clear that there is a need for a robust, continuous and persistent process of training the technicians involved in the preparation of the local plans, as well as raising the level of technical and political sensitivity to the impacts of climate change.

In the second phase of the work, the ways of implementing adaptation in spatial plans were specified and guidelines were structured with a view to integrate adaptation to the climate hazards explored in the RNA2100 in the context of the preparation of PDM. These contents are in line with the other outputs of the project and have been translated into a guide produced as part of the communication and training work package of the project, with the aim of supporting technicians and decision-makers in their mission to improve the resilience of their territories to climate impacts, in the context of their PDM development.

The municipal scale was considered to be the territorial reference for the two studies because of the importance of this scale for adaptation to climate change; furthermore, according to the legislation in force on the territorial management system, the only interventions of the local administration of normative and binding nature on private individuals are in the local spatial planning plans; and finally, because the entire national territory is covered by PDM, this being the scale at which the process of planning adaptation to climate change has most developed.

For each of the RNA2100 domains, namely droughts, water scarcity, agroforestry, rural fires and coastal areas, the guide provides information on the level of priority of the municipality in adapting to the climate related risks, frames adaptation measures for municipalities to deal with climate-related hazards, details how adaptation should be integrated into the various PDM documents, articulates adaptation measures with urban and rural land use classes and categories of the plan, identifies the main constraints in adopting adaptation measures and explores side-benefits of integrating adaptation measures. The guide also includes an introduction to climate change adaptation and how spatial planning and its instruments can contribute to ensuring adaptation.

The work carried out analysed the way in which climate policy is integrated into the objectives, guidelines, provisions and actions of the PDM and identified four dimensions for integrating adaptation into municipal plans, namely strategic, regulatory, operational and territorial governance. These dimensions were identified according to the thematic scope, scale and content (reports, regulations, maps) of the plans (Table 4.1).

Table 4.1 - Dimensions for integrating adaptation into Municipal Master Plans

Method of realisation	Stages and documents with the highest potential to integrate adaptation
Strategic Dimension	
• Define foreseeable territorial development scenarios. • Establish medium and long term sustainable development visions that incorporate the climate change component. • Define new principles for land use and occupation. • Develop benchmarking of best practices. • Implement territorial organisation guidelines that take into account the location of buildings, infrastructure and elements of the ecological network. • Adopt guidelines for the organisation of urban spaces, taking into account the	• In the **reports**, when defining climate adaptation strategies, measures and actions, as strategic options to be included in the land-use planning model. • In **characterisation studies**, when specific assessments are made for the area covered by the plan, contributing to the definition of adaptation options (bioclimatic assessments, climate hazard modelling, climate vulnerability assessment); • In **environmental reports**, consider the significance and impact of climate change as a criterion linked to critical decision factors; • In **environmental reports**, assess the significant environmental impacts (positive, negative or neutral) of adaptation measures; • In **environmental reports**, consider adaptation measures as planning and management measures to mitigate negative environmental impacts or to enhance positive impacts.

Method of realisation	Stages and documents with the highest potential to integrate adaptation
uses and morphologies of urban complexes, buildings and public spaces.	
Regulatory Dimension	
• Define legal and regulatory provisions for land use and occupation. • Deepen the regulatory framework for buildings to promote their resilience and energy efficiency.	• Modifying in the **regulations** the indexes, indicators and/or reference parameters depending on the policy options, measures and climate adaptation measures; • Including in the **regulations** the principles and rules of national, regional and inter-municipal planning plans and programmes; • Including in the **regulations** the identification of areas of public interest for expropriation, based on the spatialisation of the climate-related hazards and risks, or the need to relocate facilities; • In **graphic documents**, the reclassification of land according to the modelling of the evolution of climate hazards, strategic options, climate adaptation measures and actions, as well as the consideration of exceptional processes of reclassification from rural to urban land with associated economic potential and vice versa.
Operational Dimension	
• Identify provisions for the implementation of priority actions. • Ensure that projects are climate-proof. • Identify the public investments needed to develop, qualify and protect the territory. • Implementing public policies and economic and financial systems.	• In the **implementation programs**, giving priority to the projects of the municipality or the central administration that implement the strategic options, measures and actions for climate adaptation provided for in the planning model, as well as involving private investment in urban infrastructure. • In the **financing plans**, including investments related to projects that implement the strategic options, measures and actions for climate adaptation, promoting their effective implementation. • In the **models for the redistribution of benefits and burdens**, providing for the realisation of the investments associated with the projects implementing the strategic options, measures and actions for climate adaptation. • In the **written and graphic documents** supporting land transformation operations, identifying the operations that implement the strategic options, measures and actions for climate adaptation.
Territorial Governance Dimension	
• To raise awareness, build capacity and encourage widespread participation of citizens and relevant services at different levels of government (local,	• During the **preparation of the plans**, developing public participation and consultation processes that ensure the monitoring, articulation and incorporation of contributions

Method of realisation	Stages and documents with the highest potential to integrate adaptation
regional and national) and other interested stakeholders. • Integrate different fields of knowledge, experience and practice. • Promote policy formulation and coordination.	from the public administration, regional and local development actors and the general population. • During the **preparation and implementation/monitoring of the plans**, developing actions to raise the awareness of the public administration, regional and local development actors and the general population of the climate adaptation strategies adopted and their impact (potential or actual) on land use planning. • During the **preparation, implementation and monitoring of the plans**, promoting multi-level coordination of climate adaptation strategies with implications for land use planning.

Source: CEDRU (2023)

In addition to defining the stage and documents of the plan at which full adaptation should take place, reference practices were also identified through examples of adaptation measures included in adaptation instruments (municipal or intermunicipal adaptation plans and strategies) and PDM in force.

The first phase work and the guide are project outputs (WP7C – Review of the current panorama of adaptation to climate change in the spatial planning plans and programmes and WP8D – Guidelines and good practices for integrating adaptation into municipal master plans) and are available for download on the RNA2100 website (https://rna2100.apambiente.pt/).

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