Deliverable Phase 2 – Climate risk assessment

Comunidade Intermunicipal do Baixo Alentejo (CIMBAL)

Portugal, Baixo Alentejo

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Abbreviations and acronyms

Insert here all acronyms appearing along the deliverable in alphabetical order. This text marked in green should be deleted before submitting the deliverable.

Abbreviation / acronym	Description
AABA	Associação de Agricultores do Baixo Alentejo (Farmers Association of Baixo Alentejo)
ACOS	Associação de Criadores de Ovinos do Sul (Southern Sheep Breeders Association)
Aebal	Associação Empresarial do Baixo Alentejo e Litoral (Business Association of Baixo Alentejo and Coastal Region)
ANEPC	Autoridade Nacional de Emergência e Proteção Civil (National Authority for Emergency and Civil Protection)
AWC	Available Water Capacity
CEBAL	Centro de Biotecnologia Agrícola e Agroalimentar do Alentejo (Alentejo Agricultural and Agro-Food Biotechnology Centre)
CIMBAL	Comunidade Intermunicibal do Baixo Alentejo (Intermunicipal Comunity of Baixo Alentejo)
CLIMAAX	CLIMAte risk and vulnerability Assessment framework and toolboX
COS	Carta de Ocupação do Solo (Land Use Map)
CRA	Climate Risk Acessment
DRCNF	Direção Regional de Conservação da Natureza e Florestas (Regional Directorate for Nature Conservation and Forests – Alentejo Division of ICNF)
EBM	Empresa de Base Municipal – likely a local environmental or municipal services company (clarification may be needed)
ECLIPS	European CLimate Index ProjectionS
EDIA	Empresa de Desenvolvimento e Infraestruturas do Alqueva (Alqueva Development and Infrastructure Company)
EURO-CORDEX	Europian Coordinated Downscaling Experiment
GCM	General Circulation Model
GPP	Gabinete de Planeamento, Políticas e Administração Geral (Office of Planning, Policies and General Administration)
ICNF	Instituto da Conservação da Natureza e das Florestas (Institute for Nature Conservation and Forests)
LST	Land Surface Temperature

MACAT	Mapa Anual de Culturas Agrícolas Temporárias (Annual Map of Temporary Agricultural Crops)
MAP	Mean Annual Precipitation
MAT	Mean Annual Temperature
NDVI	Normalized Difference Vegetation Index
Nerbe	Núcleo Empresarial da Região de Beja (Business Association of the Beja Region)
PARs	Planos de Adaptação Municipais (Municipal Adaptation Plans)
PIAAC-BA	Plano Intermunicipal de Adaptação às Alterações Climáticas do Baixo Alentejo (Baixo Alentejo Intermunicipal Climate Change Adaptation Plan)
RCM	Regional Climate Model
RCP	Representative Concetration Pathway
SHM	Summer Heat-Moisture index

Executive summary

This deliverable presents the Phase 2 Climate Risk Assessment (CRA) for the Intermunicipal community of Baixo Alentejo (CIMBAL), developed under the CLIMAAX framework and building on the Phase 1 deliverable. Phase 2 strengthens decision usefulness by regionalising the Phase 1 workflows with higher-resolution and nationally/locally relevant datasets, refining modelling choices, and producing outputs that can be interpreted at intermunicipal and municipal scales. The assessment focuses on three priority risks confirmed through stakeholder engagement: heatwaves, agricultural drought, and rural wildfires.

Phase 2 targeted the main limitations identified in Phase 1. For rural wildfires, the hazard modelling approach was recalibrated to Portuguese conditions to improve sensitivity to climate drivers and to provide clearer temporal evolution, and the risk assessment was extended with operationally relevant indicators reflecting response constraints, including accessibility and water-point coverage. For heatwaves, methodological continuity was maintained through the EuroHEAT criterion, while the analysis was sharpened by aggregating outputs to decision-relevant units and adding remote-sensing diagnostics (land surface temperature and vegetation metrics) to characterise within-town exposure patterns and cooling potential linked to green infrastructure. For agricultural drought, the analysis was aligned with the regional crop profile and yield-loss outputs under rainfed assumptions were translated into monetary loss (€/ha) using locally referenced productivity and price values.

Results indicate intensification of all three hazards under both RCP 4.5 and RCP 8.5. Heatwave projections show strong increases in heatwave-day frequency, with recurrent hotspots where hazard increases coincide with higher densities of vulnerable age groups, and the urban diagnostics show consistent cooling associated with vegetated areas and measurable cooling influence into adjacent built-up fabrics. Agricultural drought results show crop-dependent yield penalties and economically meaningful losses in key production areas, while underlining the need to represent irrigated versus rainfed management and water allocation constraints more explicitly. Wildfire projections show increasing hazard over successive future periods, particularly under RCP 8.5, and risk priorities vary by receptor (population, infrastructure, ecological value) and by operational constraints.

Overall, heatwaves and agricultural drought emerge as the most severe and urgent risks for Baixo Alentejo, given their current relevance and projected worsening, while rural wildfires require targeted prioritisation where increasing hazard intersects critical assets, high-value ecosystems, or constrained response capacity. Phase 3 will translate the Phase 2 risk picture into a prioritised portfolio of adaptation measures and monitoring triggers, validated with stakeholders and aligned with regional and municipal planning instruments.

1 Introduction

1.1 Background

The Baixo Alentejo is a sub-region of the Alentejo Region, covering a vast area of approximately 8,544.6 km², located in the southeastern quadrant of mainland Portugal, within the Alentejo region. Administratively, the sub-region falls within the district of Beja and comprises 13 municipalities, all characterized by low population density: Aljustrel, Almodôvar, Barrancos, Beja, Castro Verde, Cuba, Ferreira do Alentejo, Mértola, Moura, Ourique, Serpa, and Vidigueira. These municipalities form part of the Intermunicipal Community of Baixo Alentejo – CIMBAL.

Climatically, Baixo Alentejo is classified as a Mediterranean climate region, characterized by a high annual average temperature. The interior experiences significant temperature variations, with days exceeding 25ºC for more than a third of the year. Annual rainfall is unevenly distributed, with most precipitation occurring in autumn and winter, while there is a marked shortage of rainfall in summer. As such, the region is known for its hot, dry summers and mild winters, making it particularly vulnerable to climatic extremes.

Recognized for its strong cultural, natural, and scenic identity, the Baixo Alentejo territory is dominated by vast plains and extensive agricultural and forestry production areas. This land use is encouraged not only by the favorable climate and geographical conditions but also by the Alqueva hydro-agricultural infrastructure. The rural characteristics of the region are inseparable from its identity. Therefore, the region is predominantly rural, with low population density and a heavy reliance on agricultural, livestock, and forestry economic activities.

One of the primary sources of income in Baixo Alentejo is closely associated with seasonal economic activities, such as agriculture, especially in the more rural areas far from the main municipal centers. These incomes are often unstable due to the climatic changes that have increasingly affected the region.

The Guadiana River, one of Baixo Alentejo's most important natural resources, is an international river in the Iberian Peninsula that originates in Spain. Upon reaching Portugal in the Alentejo, it runs along the border. Its landscapes, of significant historical and natural value, bear witness to human action over time, which has transformed the original natural cover into a variety of ecosystems adapted to the region's dryness and aridity.

This sub-region is deeply marked not only by its cultural heritage but also by its natural heritage, including examples such as the Special Protection Areas of Moura, Barrancos, and Guadiana, as well as the Guadiana Valley Natural Park.

In recent decades, Baixo Alentejo has experienced an increase in climate-related phenomena, particularly droughts, heatwaves, and wildfires. These events have had substantial impacts on water availability, agricultural yields, biodiversity, and the well-being of local communities. Climate projections for southern Portugal suggest that these risks are likely to intensify, with higher temperatures, reduced annual precipitation, and longer dry seasons. These evolving conditions present serious challenges to sustainable land and water management, underscoring the need for structured and regionally adapted climate risk assessments.

1.2 Main objectives of the project

Phase 2 of the CLIMAAX–Baixo Alentejo project deepens and regionalizes the Climate Risk Assessment developed in Phase 1, maintaining the focus on agricultural drought, rural wildfires, and heatwaves as the priority climate risks for the region. Building on the CLIMAAX framework and the initial workflows, this phase aims to produce a more detailed and locally grounded understanding of how these hazards translate into risk through the interaction of hazard dynamics, exposure patterns, and vulnerability drivers across Baixo Alentejo.

More specifically, Phase 2 pursues the following objectives:

- Refine hazard and risk assessments for agricultural drought, wildfires, and heatwaves by fine-tuning CLIMAAX workflows to Portuguese and Baixo Alentejo conditions, using higher-resolution and nationally produced datasets, and updated modelling approaches (including improved wildfire susceptibility modelling and locally relevant drought and heat indicators).
- Integrate local methodologies, data, and models into the CLIMAAX backbone to increase representativeness and decision usefulness—e.g., locally mapped crop systems and reference values for drought impacts, land-use information to support wildfire and heat analyses, and remote-sensing metrics to characterize urban thermal patterns.
- Deliver stakeholder-prioritized risk outputs, translating workshop and survey priorities into targeted analyses such as identifying hotspots of hazard intensification, assessing the exposure of critical assets and service areas, and detailing vulnerability patterns relevant for civil protection, land management, water, agriculture, and public health planning.
- Strengthen regional decision support by producing indicators and maps that are directly usable within intermunicipal and municipal instruments, supporting risk-informed prioritization and resource allocation.
- Prepare the analytical basis for Phase 3, ensuring Phase 2 results can be translated into concrete adaptation options and management measures to be co-developed and prioritized with stakeholders in the final phase.

The CLIMAAX Handbook and toolbox remain central to Phase 2: they provide a harmonized methodological structure, while the systematic inclusion of local datasets and region-specific refinements enables the assessment to remain comparable across Europe and, at the same time, deliver **decision-ready evidence tailored to Baixo Alentejo**.

1.3 Project team

The Phase 2 climate risk assessment for CIMBAL was delivered through a joint team combining (i) CIMBAL's coordination and stakeholder facilitation capacity across the 13 municipalities and regional entities and (ii) greenmetrics.ai as the technical analysis partner responsible for data engineering, GIS processing, climate-indicator handling, modelling, and map/dashboard production. Technical work covered the three priority risks (heatwaves, agricultural drought, and rural wildfires), including regionalisation of CLIMAAX workflows, integration of Portuguese/local datasets, and development of additional indicators (remote-sensing urban heat diagnostics; drought monetary loss metrics; wildfire response-capacity proxies). Stakeholder engagement and validation were supported through dedicated workshops and continuous coordination with sectoral institutions (civil protection, forestry/environment, water/irrigation, agriculture, research, and municipal services).

1.4 Outline of the document's structure

This deliverable is organized into six main sections:

Section 1- Introduction

Provides a short summary of the region's background, main goals for the implementation of the CLIMAAX framework and project team.

Section 2 – Climate Risk Assessment - Phase 2

Provides a detailed analysis of climate risks affecting Baixo Alentejo, including hazard screening, scenario selection and risk analysis methodologies.

Section 3 – Key Findings

Summarizes the preliminary results of the assessment, including identified risks, vulnerabilities, and potential issues requiring future adaptation strategies.

Section 4 – Monitoring and Evaluation

Discusses the mechanisms for tracking progress, refining risk assessments, and integrating stakeholder feedback.

Section 5 – Conclusions

Presents the key conclusions from the preliminary climate risk assessment, reflecting on the main results obtained with this methodology and its limitations.

Section 6 – Supporting Documentation

Includes references, datasets, and supplementary materials used in the assessment.

2 Climate risk assessment – Phase 2

2.1 Scoping

2.1.1 Objectives

The objective of the Phase 2 climate risk assessment (CRA) for Baixo Alentejo is to refine and regionalize the foundational analysis produced in Phase 1, strengthening the understanding of the region's exposure and vulnerability to heatwaves, agricultural drought and wildfires. Building on the CLIMAAX framework, Phase 2 focuses on integrating higher-resolution and locally validated datasets and methods, with the expected outcome of producing more locally representative hazard and risk outputs and clearer evidence to support risk prioritization and subsequent adaptation planning.

The CRA is intended to contribute directly to regional policy and decision-making by improving the usability of risk information for municipal and intermunicipal planning, civil protection preparedness, and sector-specific adaptation actions (notably for climate-sensitive rural systems and vulnerable population groups). In Phase 2, the CLIMAAX workflows were explicitly fine-tuned using **local land** use/land cover and agricultural data and complemented with additional indicators derived from remote sensing and region-specific modelling choices, so that the resulting maps and metrics can better inform the design, targeting, and justification of adaptation measures aligned with national guidelines and EU directives.

In Phase 2, key limitations identified in Phase 1 were partially addressed through the incorporation of local datasets (e.g., updated land-use mapping and crop-specific productivity/value references), enabling a more realistic representation of Baixo Alentejo's production systems and improving the interpretability of results. Remaining boundaries and challenges still include uncertainty associated with climate projections and scenario assumptions, constraints in representing irrigated vs. rainfed conditions consistently across the territory, and the need to further consolidate stakeholder-driven validation and operational thresholds for risk interpretation. Despite these constraints, the Phase 2 CRA provides a more robust and locally grounded basis for iterative risk analysis and for the Phase 3 transition from assessment to prioritize adaptation pathways.

2.1.2 Context

The Baixo Alentejo region is highly sensitive to climate variability, with a historical record of intense heatwaves, severe droughts, and, consequently, wildfires. Its Mediterranean climate results in long, dry summers and rising temperatures, which have been intensifying and worsening in recent years, thereby exacerbating water scarcity and fire risk.

As a result of the increased intensity and severity of recent climatic events, there has been a noticeable decline in agricultural productivity, an overburdening of water resources that has both triggered and aggravated the region's ongoing desertification. Simultaneously, wildfire activity has intensified, particularly in rural and forest-adjacent areas, in the southern part of the Baixo Alentejo territory, where accessibility challenges hinder effective fire response.

In order to address these issues and promote adaptation to climate change, the Intermunicipal Community of Baixo Alentejo (CIMBAL), which integrates 13 municipalities (Aljustrel, Almodôvar, Barrancos, Beja, Castro Verde, Cuba, Ferreira do Alentejo, Mértola, Moura, Ourique, Serpa, and Vidigueira) developed, in 2018, a fundamental strategic instrument for the region the Baixo Alentejo Intermunicipal Plan for Climate Change Adaptation (PIAACBA). This plan lists a series of priority actions designed to better prepare the region for the climate changes it faces. Following CIMBAL's example, some of the municipalities in the region have developed their own Climate Change Adaptation Plans (PARs), addressing local vulnerabilities in greater detail. More recently, some municipalities have also prepared their Municipal Climate Action Plans.

All these efforts are aligned with national policies across sectors such as agriculture, forestry, water, and civil protection. However, despite the progress made, gaps remain in local coordination, technical capacity, and data integration, significantly limiting the effective implementation and development of the identified adaptation actions.

Given this reality, it is possible to identify the economic sectors most affected, and consequently the most critical, by climate change such as agriculture, forestry, rural development, and water supply. The large and extensive agroforestry areas in the region and reliance on rainfed cultivation, significantly increase vulnerability to drought and fire. Structural issues such as rural depopulation, ageing infrastructure, and economic dependence on climate-sensitive sectors further increase the impact of climate change on the region.

2.1.3 Participation and risk ownership

Stakeholder participation is a critical component of the climate risk assessment for Baixo Alentejo, ensuring that risk ownership is distributed across key entities responsible for land management, emergency response, environmental conservation, and public health.

To establish an inclusive and effective engagement process, a diverse set of stakeholders was identified and invited to participate in the project. This initial list includes representatives from governmental agencies, municipalities, research institutions, forestry and agricultural associations, civil protection organizations, and community-based groups. Recognizing that climate adaptation requires ongoing collaboration, this stakeholder network is expected to expand as the project progresses.

Stakeholder engagement began with a regional workshop held on 27 January 2024. This event was the first structured interaction with stakeholders and aimed to gather local insights on climate-related vulnerabilities and risk perception, with a specific focus on heatwaves, agricultural drought and wildfires.

This workshop provided a platform for participants to contribute insights, validate preliminary findings, and highlight critical data gaps. Additionally, it offered an opportunity to align analytical efforts for Phase 2 of the project, ensuring that stakeholder-provided data and objectives are effectively integrated into the next stages of climate risk modeling and decision-support frameworks.

Table 2-1 Mapped Stakeholders

Type / Sector	*Stakeholders*
Municipalities	Aljustrel, Almodôvar, Alvito, Barrancos, Beja, Castro Verde, Cuba, Ferreira do Alentejo, Mértola, Moura, Ourique, Serpa, Vidigueira
Agriculture and Livestock Associations	ACOS / AABA
Business and Economic Development	Nerbe / Aebal
Agricultural and Biotech Research	CEBAL
Forestry and Conservation Authorities	DRCNF, ICNF
Civil Protection	ANEPC

Type / Sector	*Stakeholders*
Environment and Energy Management	EBM
Water and Irrigation Infrastructure	EDIA

This group represents a wide range of governance levels, technical and scientific expertise, and sectoral interests including agriculture, environment, forestry, and emergency management. Their early contributions were instrumental in validating the relevance of the selected risks and initiating a coordinated approach to data gathering.

2.1.4 Application of principles

Social justice, equity, inclusivity: The assessment design explicitly considered who is most affected and least able to cope, and ensured that risk interpretation supports targeted action. For heatwaves, vulnerability mapping prioritized age-related sensitivity (children and older adults) and the analysis was refined to settlement/urban scales to better represent where exposure concentrates. For agricultural drought and wildfires, the Phase 2 focus incorporated rural livelihoods and service constraints (e.g., crop-dependent losses; accessibility and water-point coverage relevant to emergency response), reflecting stakeholder-identified priorities and the territorial reality of dispersed communities. Participation was organized to include municipalities and regional institutions covering public health, civil protection, forestry/environment, agriculture, and water management, supporting inclusivity across sectors and governance levels.

Quality, rigour, transparency: Phase 2 strengthened rigour by maintaining continuity with CLIMAAX indicators where appropriate,upgrading model choices and calibration where Phase 1 limitations were, and replacing generic proxies with nationally/locally relevant datasets. Methodological choices, assumptions, and dataset provenance were documented in the workflow descriptions and data tables to ensure traceability and reproducibility, and the outputs prepared for sharing through the project repository consistent with CLIMAAX reporting expectations.

Precautionary approach: A precautionary framing was applied by consistently analyzing both a medium stabilization pathway and a high-emissions pathway (RCP 4.5 and RCP 8.5), and by interpreting ensemble outputs as tendencies under uncertainty rather than deterministic forecasts. For wildfire hazard, additional mechanisms were introduced to ensure that hazard evolution follows the projected direction of key climate drivers, reducing misleading artefacts in far-future slices. For planning relevance, the assessment emphasizes “low-regret” priorities (hotspots where hazard intensification aligns with vulnerable receptors or constrained response capacity), supporting early action even under uncertainty.

2.1.5 Stakeholder engagement

Stakeholder engagement in the CLIMAAX–Baixo Alentejo project has been organized primarily through in-person workshops aimed at validating the relevance of the selected hazards, identifying data gaps, and guiding improvements to the analytical workflows between Phase 1 and Phase 2.

A first regional workshop was held during Phase 1 to present the CLIMAAX methodology and the preliminary risk assessment results, and to collect feedback on priorities for Phase 2. The workshop also included a structured prioritization exercise (via a QR-code survey), where participants scored candidate analysis lines using criteria such as regional relevance and expected data availability.

Participants included representatives from the 13 municipalities of Baixo Alentejo and key sectoral/regional entities linked to risk ownership and adaptation planning, including actors from agriculture and livestock, business and economic development, research organizations, forestry and conservation authorities, civil protection, and water/irrigation infrastructure management.

During Phase 2, a follow-up workshop (19/11/2025) was conducted to review the prioritized analysis lines and communicate the methodology and intermediate technical results, as well as to present the planned next steps towards Phase 3. Overall, results were received positively, with constructive feedback focused on improving the representativeness of local conditions and strengthening the link between risk outputs and operational decision-making. This feedback has supported the refinement of Phase 2 analyses and the identification of additional local datasets and methodological extensions.

Stakeholder engagement has also highlighted practical challenges, including: (i) limitations in the direct applicability of some European-scale datasets to local realities, and (ii) the need to coordinate inputs across multiple institutions with different data ownership and capacity levels. These constraints reinforce the importance of maintaining an iterative engagement process, using workshops and targeted exchanges to validate assumptions, improve data integration, and ensure that the final project outputs are usable within ongoing regional and municipal planning instruments.

2.2 Risk Exploration

2.2.2 Screen risks (selection of main hazards)

The initial screening of climate risks in Baixo Alentejo identified three priority hazards: heatwaves, droughts, and wildfires. These were selected based on historical evidence, stakeholder feedback, and alignment with existing strategic plans, including the PIAAC-BAL and municipal-level PARs.

Heatwaves are an emerging climate hazard in the region, both as a compounding factor in wildfire risk and as a direct threat to public health, labor productivity, and infrastructure. Increasing frequency, intensity, and duration of heatwaves in recent decades have been observed, with implications for vulnerable populations, especially the elderly isolated people and those working in outdoor sectors such as agriculture and construction.

Droughts are a recurrent and increasingly severe phenomenon in the region, with major implications for agriculture, water availability, and ecosystem and biodiversity. Projected reductions in precipitation, coupled with higher evapotranspiration rates, threaten both rainfed and irrigated farming systems, as well as surface and groundwater reserves.

Wildfires have growingly become a climate risk threatening the Alentejo region, particularly during the dry summer season. Contributing factors include high fuel loads, extreme heat, land abandonment, and limited accessibility for firefighting. Climate change is expected to intensify these conditions by increasing the frequency of heatwaves and prolonging drought periods.

All three risks were confirmed as relevant through the stakeholder workshop held in January 2024. Participants reinforced the urgency of addressing these hazards and highlighted their interrelated impacts on land use, economic stability, and social vulnerability.

In addition to the three selected risks, several stakeholders working in climate change policy and implementation also expressed concern over the increasing frequency and severity of extreme weather phenomena, particularly strong wind events and episodes of intense precipitation. Although not chosen for detailed assessment in Phase 1, these hazards were recognized as emerging threats that warrant further monitoring and may be incorporated into the CRA's scope in future project phases.

Preliminary data analysis corroborated these concerns. For heatwaves, observed temperature records and projected increases in extreme heat days point to escalating stress on both human health and ecological systems. For droughts, soil moisture indices, precipitation anomalies, and agricultural yield projections indicate persistent and intensifying stress on productive land. For wildfires, historical burn area records and predictive modelling using RCP scenarios suggest an upward trend in fire risk across most of the territory.

While these three risks are the primary focus of Phase 1, other climate hazards—such as floods and storms—may be explored in future phases, particularly if new data or stakeholder input supports their relevance.

2.2.3 Choose Scenario

Future climate conditions considered and rationale Phase 2 considered two climate pathways to bracket plausible futures and support precautionary decision-making: RCP 4.5 (stabilisation/mitigation-consistent trajectory) and RCP 8.5 (high-emissions, more adverse trajectory). These scenarios are consistent with the CLIMAAX workflows and with the available climate-driven hazard datasets used in the analyses (EURO-CORDEX-derived heatwave indicators and ECLIPS2.0-based wildfire predictors).

Future socio-economic developments considered Phase 2 did not include explicit future socio-economic projections (e.g., SSP-based trajectories for population, economic activity, land-use change, or food demand/prices). Exposure and vulnerability layers therefore represent a mostly static baseline using the most recent available datasets. Stakeholder engagement was used to support interpretation of results and to flag where socio-economic dynamics (e.g., demographic ageing, irrigation management and allocation constraints, and land-use/fuel changes) could influence future impacts, but these dynamics were not modelled quantitatively in Phase 2.

How climate and socio-economic developments were combined The analytical combination followed the CLIMAAX risk logic: climate scenarios drive the hazard evolution, which is then overlaid with exposure and vulnerability layers to produce relative risk patterns and rankings. In practice, future climate conditions (by RCP and time slice) were combined with mostly static exposure and vulnerability baselines to isolate the climate signal on hazard and risk.

Time horizons considered Time horizons reflect the structure of the underlying datasets and the decision needs discussed with stakeholders, covering near- to long-term planning:

- Heatwaves (EURO-CORDEX indicator): near future 2016–2045 and mid-century 2046–2075, assessed under RCP 4.5 and RCP 8.5.
- Rural wildfires (ECLIPS2.0-driven modelling): 2021–2040, 2041–2060, 2061–2080, and 2081–2100 under RCP 4.5 and RCP 8.5.
- Agricultural drought (crop water balance / yield-loss approach): scenario application consistent with the Phase 2 implementation presented to stakeholders, using the time periods 2026–2030, 2031–2035, 2036–2040, 2041–2045, and 2046–2050, complemented by historical soil-water capacity context used as baseline conditioning.

2.3 Regionalized Risk Analysis

2.3.1 Hazard #1: Wildfires - fine-tuning to local context

Table 2-2 Data overview workflow #1

Hazard data	*Vulnerability data*	*Exposure data*
Climatic variables (Chakraborty, et al. 2020)	Population (Copernicus Emergency Management Service s.d.)	Main Roads - *internal documentation of CIM*
Land types (Direção-Geral do Território 2025)	Ecological- (Copernicus Emergency Management Service s.d.)	Healthcare Services - internal documentation of CIM
Topography (Gonçalves s.d.)	Economical- (Copernicus Emergency Management Service s.d.)	Urban zones - internal documentation of CIM
Historic Wildfires (Instituto da Conservação da Natureza e das Florestas 2025)	Water points - internal documentation of CIM	Elderly care homes - internal documentation of CIM
Susceptibility of land types to wildfires (Instituto da Conservação da Natureza e das Florestas 2020)	Strategic Parking Locations - internal documentation of CIM	Schools - internal documentation of CIM

2.3.1.1 Hazard assessment

The wildfire hazard assessment developed in Phase 2 builds on the CLIMAAX machine-learning wildfire workflow but is now explicitly calibrated to Portuguese conditions and refined for the Baixo Alentejo context. The main objective is to produce hazard maps that (i) better reflect projected climate trends and (ii) remain sensitive to local land-use and topographic controls, addressing key limitations identified in Phase 1, where projected climatic change was only weakly expressed in the resulting hazard patterns.

In Phase 2, an XGBoost gradient-boosting model was adopted in place of the random forest used in Phase 1. This modelling choice enables more flexible calibration and more explicit control of the model response to climate drivers, while remaining well suited to national-scale training datasets. To improve model robustness and reduce sensitivity to local class imbalance, the susceptibility model was re-trained using a Portugal-wide training domain based on synoptic wildfire events from 1991–2010 and a more focused set of predictors. Training at national scale allows the model to learn from a broader range of climatic and landscape conditions, strengthening the estimated relationships between wildfire occurrence and the predictor space before regional interpretation in Baixo Alentejo.

Climatic predictors were derived from the ECLIPS2.0 dataset and reduced to three variables that are informative for ignition and spread conditions: a summer heat–moisture index (SHM), mean annual precipitation (MAP), and mean annual temperature (MAT). These climatic drivers were complemented by higher-resolution geographical predictors that influence fuel availability and fire behavior at regional scale, including land cover (COS-2023 reclassified into fuel-relevant categories), elevation, slope, aspect, terrain roughness, and historical burnt area information used to characterize where fires have effectively occurred under past conditions.

Compared with Phase 1 where land cover and topography tended to dominate and the hazard signal showed limited temporal evolution, the Phase 2 implementation introduces climate-alignment mechanisms (including monotonic constraints) to ensure that, for a given location, hazard evolves consistently with the projected direction of change in temperature, precipitation, and the heat–moisture index. In practice, this reduces spurious decreases in far-future periods observed in some Phase 1 experiments and yields a more coherent progression of hazard intensification over time.

For each GCM–RCM combination available in ECLIPS2.0, the model was run separately to generate a set of hazard maps under alternative climate projections. A mean ensemble of these results was then computed to summarize the temporal evolution of wildfire hazard. The ensemble should be interpreted as an indication of the overall tendency under climate change rather than a precise forecast; uncertainty should be assessed by considering both the ensemble mean and the spread across individual GCM–RCM realizations.

As an additional consistency check, the resulting hazard maps were compared with ICNF structural hazard products, which remain a key operational reference for wildfire risk management in Portugal. The intention is not to replace ICNF products, but to complement them by providing a long-term perspective on hazard evolution under different climate scenarios.

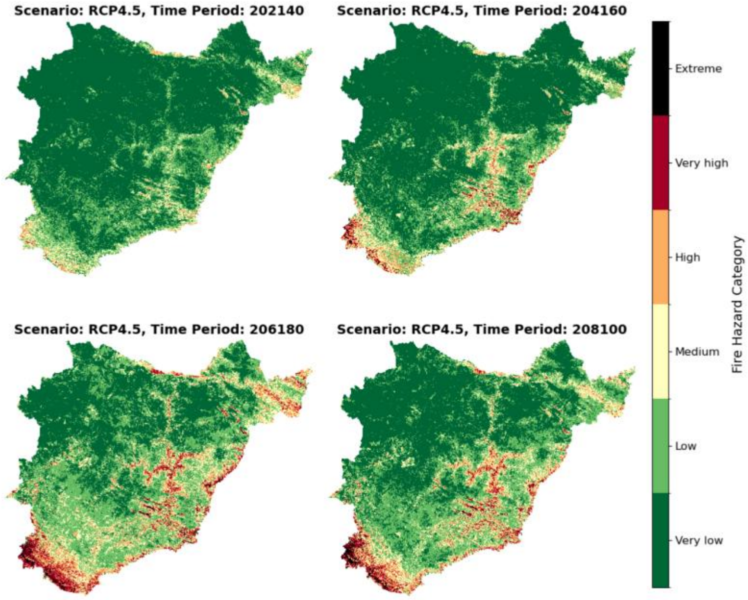

Figure 2-1 Wildfire Hazard; Scenario RCP 4.5; Periods 2021-2040, 2041-2060, 2061-2080, 2081-2100.

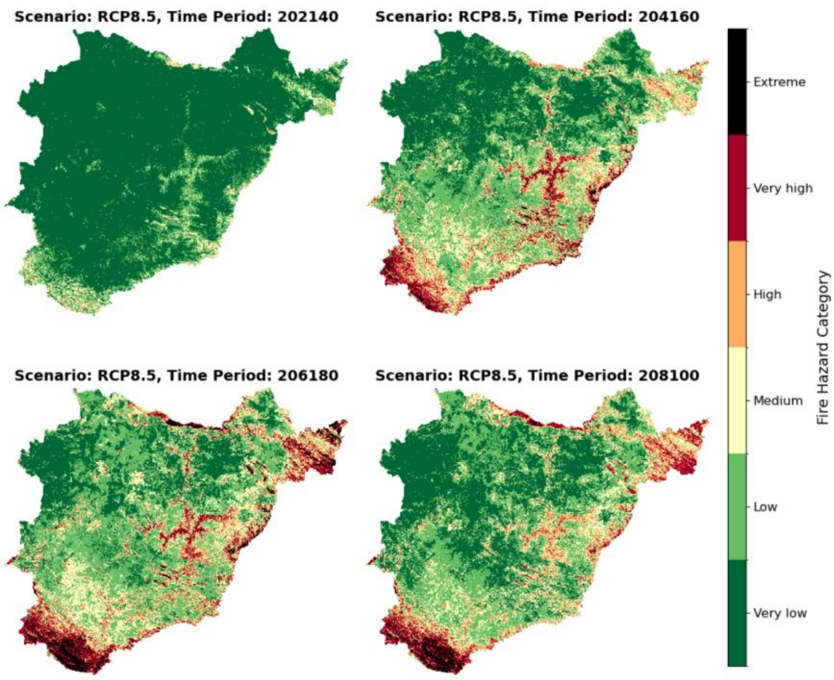

Figure 2-2 Wildfire Hazard; Scenario RCP 8.5; Periods 2021-2040, 2041-2060, 2061-2080, 2081-2100.

Overall, the Phase 2 hazard outputs are more consistent with local expectations and known structural patterns: the areas highlighted as most susceptible align more closely with the spatial logic of Portuguese wildfire hazard, and the RCP 8.5 pathway produces systematically more adverse projections than RCP 4.5. The maps also show clearer temporal evolution, with increasing hazard levels across successive future periods. The strongest increases tend to occur where land cover shifts towards more flammable vegetation types and/or where steep terrain coincides with dense and continuous fuels. Conversely, areas with more fragmented fuels or lower structural hazard tend to retain comparatively lower hazard levels even under more adverse climate trajectories. The main outputs are presented in the wildfire hazard maps (Figure 2-1and Figure 2-2), which illustrate the spatial distribution of hazard classes and their evolution over time.

Several limitations should be noted. First, the temporal granularity of training data remains constrained: the model is calibrated using a single historical reference period and then applied to future time slices. Ideally, multiple historical windows with comparable duration would be available to better characterize temporal evolution under observed variability, but this is limited by historical wildfire data availability and quality constraints. Second, some input datasets may contain local artefacts (e.g., land-cover classification issues) that can influence fine-scale model performance and the detailed hazard pattern. Despite these limitations, the datasets are considered broadly representative for regional-scale interpretation. Future work could include more systematic validation of land-cover information and/or the integration of additional local datasets to further strengthen the robustness of the hazard assessment.

2.3.1.2 Risk assessment

The wildfire risk assessment in Phase 2 combines the updated hazard maps described in Section 2.3.1.1 with exposed assets and vulnerability information to identify where wildfires are most likely to generate significant impacts on people, infrastructure, ecosystems, and economic activities. This supports stakeholders in prioritizing prevention and adaptation measures in Baixo Alentejo.

In line with the CLIMAAX workflow logic, the risk analysis follows the same time slices and emission pathways considered in the hazard assessment. For each period and for both RCP 4.5 and RCP 8.5, the ensemble wildfire hazard index is overlaid with exposure layers to produce risk indicators for the region. Compared with Phase 1, Phase 2 places greater emphasis on fine-resolution, locally validated datasets and incorporates additional exposure layers identified as relevant during stakeholder engagement, including (among others) water points relevant for suppression operations.

Infrastructure exposure is assessed by intersecting hazard outputs with key asset layers. For transport infrastructure, the exposure of the primary road network (national roads, motorways, and other major routes) is analyzed to identify segments more likely to be affected by future wildfires, with implications for evacuation, emergency response, and continuity of economic activities. Similar overlays are conducted for other critical infrastructures.

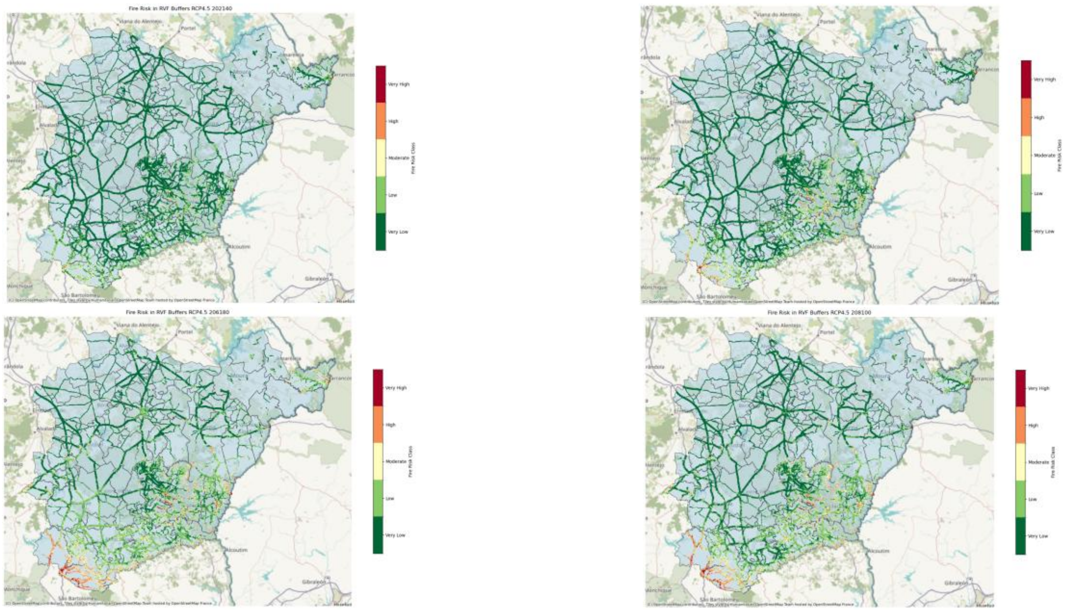

Figure 2-3 Road Network Risk.

Beyond the location of assets, the assessment integrates vulnerability dimensions (population, ecological, and economic) using the available vulnerability indicators. Vulnerability variables are classified into three classes (based on quantiles) and combined with the six hazard classes through the risk matrix (Figure 2-4). The resulting composite risk is presented in Figure 2-5.

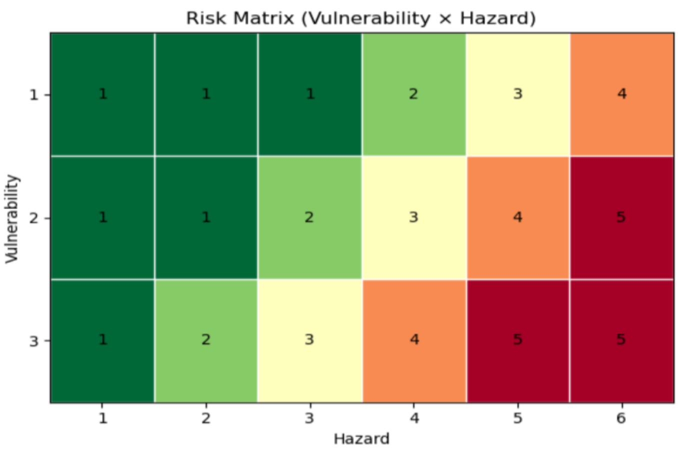

Figure 2-4 Risk Matrix used with population, economical and ecological vulnerability.

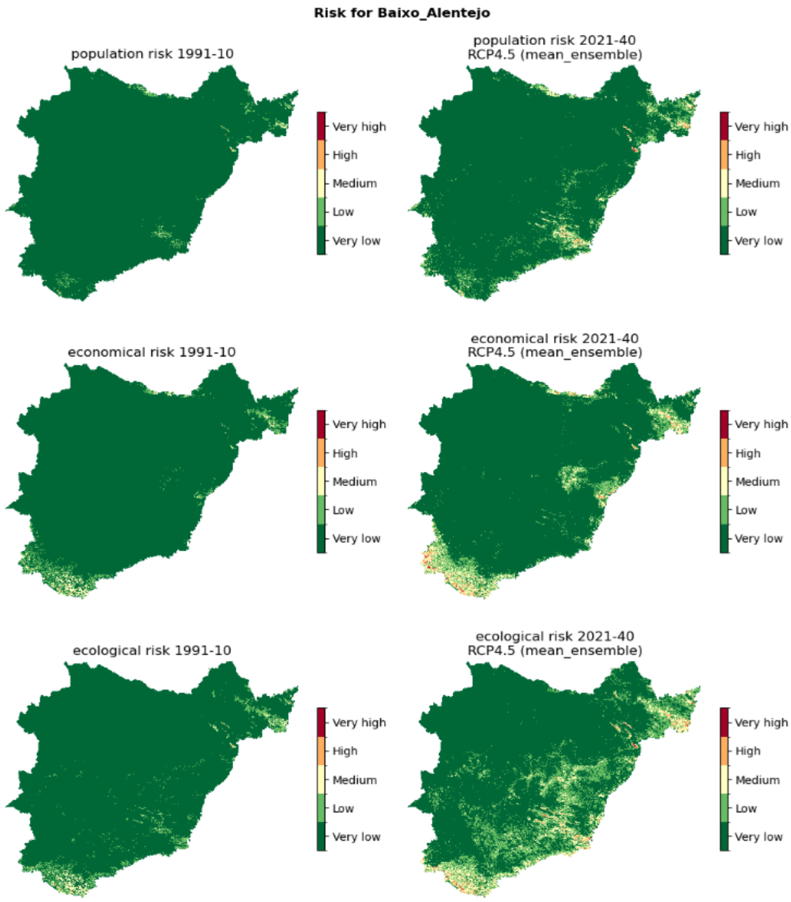

Figure 2-5 Population, economical, ecological Risk for periods 1991-2010 and 2021-2040.

Interpreting the combined outputs highlights that areas of high hazard do not necessarily translate into high risk for all receptors. Areas with comparatively low built-asset exposure and lower resident population may still emerge as high priority from an ecological perspective, particularly where high hazard overlaps protected and high-value ecosystems. Conversely, areas with higher concentrations of settlement and infrastructure can concentrate higher societal and economic risk even where hazard is similar, due to higher exposure and vulnerability.

To complement hazard-and-exposure risk, response capacity is assessed to reflect the ability to suppress fires and limit damages. Two main components are considered: coverage and accessibility of water points and; distance (or travel time) to fire stations and strategic parking areas for firefighting resources. Coverage and accessibility metrics are classified into five response-capacity classes (quantiles), where lower classes correspond to better expected response capacity. These response-capacity classes are then combined with wildfire hazard through a risk matrix (Figure 2-6) to identify areas where high hazard coincides with constrained operational response.

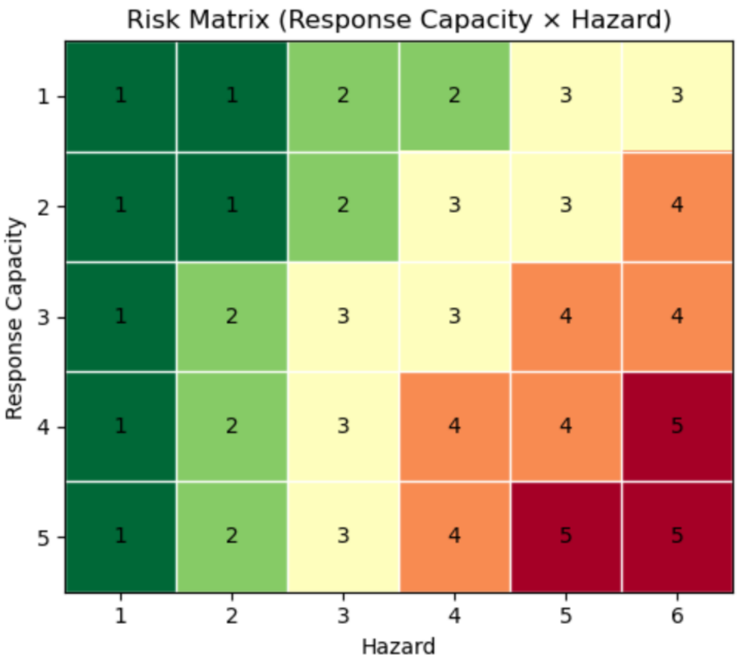

Figure 2-6 Risk Matrix used with response capacity metrics.

For water points, separate analyses are conducted for aerial and terrestrial suppression. For aerial resources, water points are assigned operating radii (e.g., 5 km and 10 km) to represent different operating ranges, and a coverage metric is derived by combining distance and stored volume. To avoid large reservoirs dominating the representation, two complementary variants are used: (i) a capped-volume metric to 10,000 m³ (Figure 2-7) that emphasizes the value of multiple medium points, and (ii) an uncapped metric visualized on a logarithmic scale (Figure 2-8) that preserves the visibility of both low- and high-volume sources while reducing contrast at the upper range. This indicator should be treated as a first-order approximation, as local terrain constraints for aerial operations (e.g., orography) are not explicitly modelled.

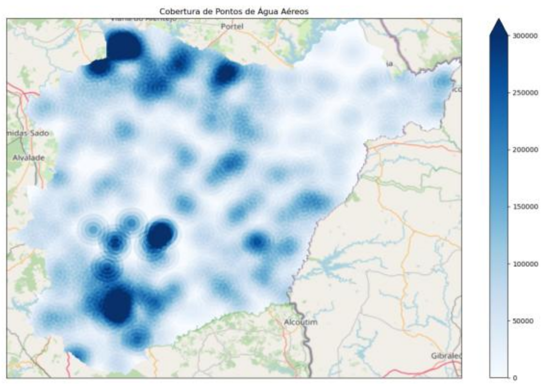

Figure 2-7 Aerial water points capacity with a limit of volume 10000 m3 and a limit of radius of 5 km for each water point. (i)

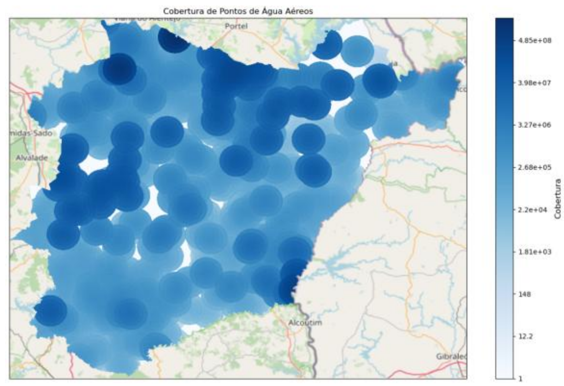

Figure 2-8 Aerial water points capacity with logarithmic scaling and a limit of radius of 5 km. (ii)

The resulting risk of the water points capacity for each of the methods (i) and (ii) is then presented in Figure 2-9 and Figure 2-10, respectively. For both methods the risk is situated mostly on the northwest region of CIMBAL.

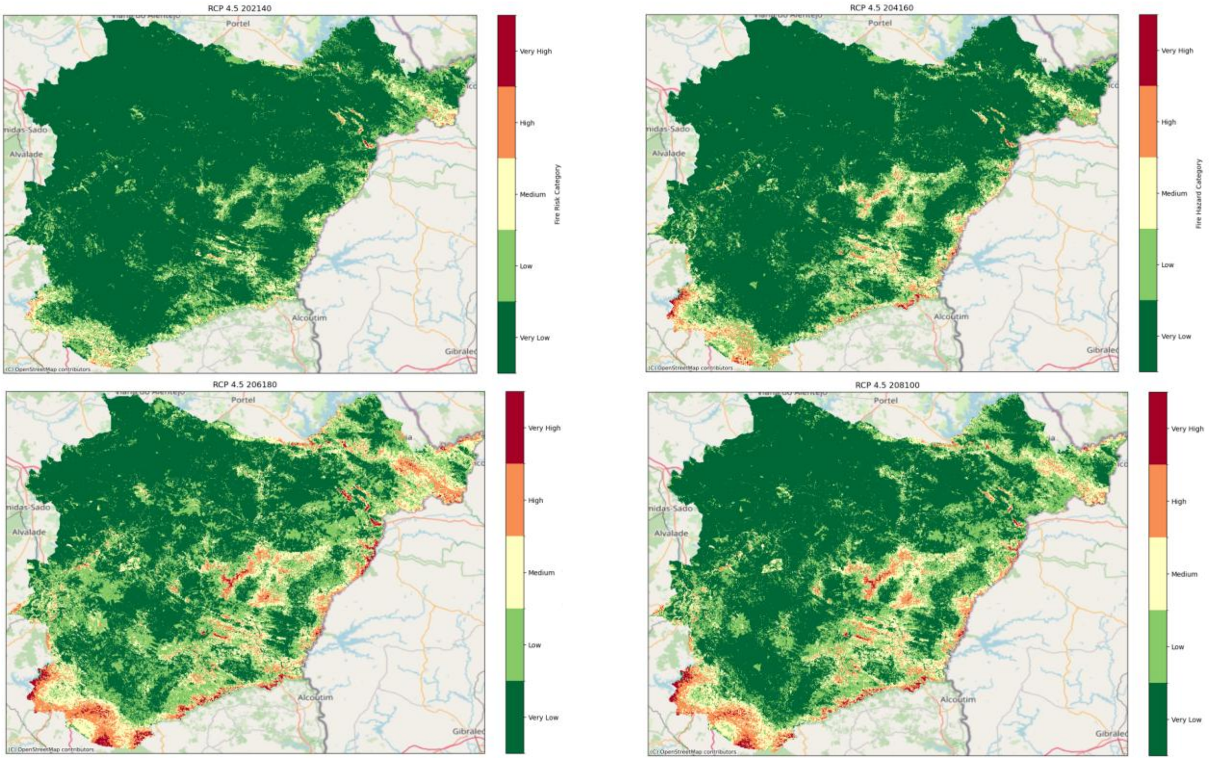

Figure 2-9 Risk of wildfire taking into consideration Aerial Water Points capacity with a limit of 10000 m3.

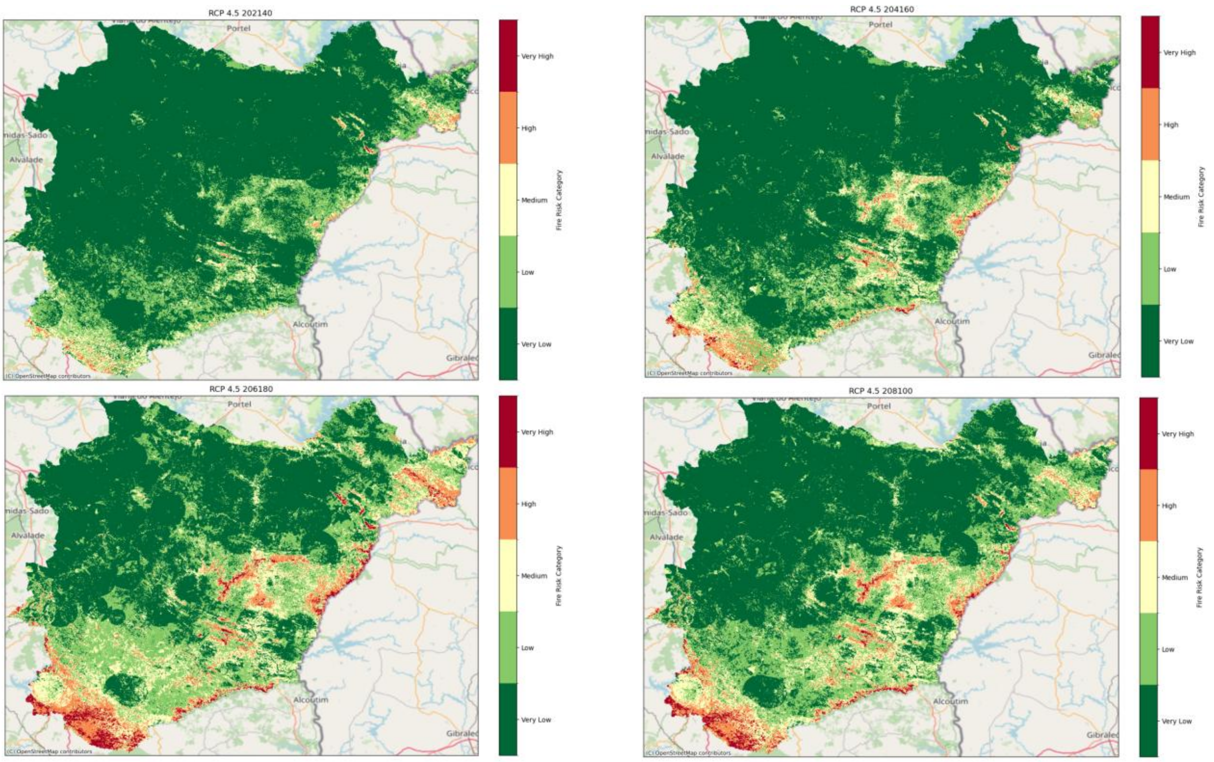

Figure 2-10 Risk of wildfire taking into consideration Aerial Water Points capacity with a logarithmic Scaling.

For terrestrial suppression, coverage is assessed through routing on the road network, producing distance and travel-time indicators to the nearest terrestrial or mixed-use water point (without considering stored volume). Subsequently, this distance was categorized and then matched with the hazard data resulting in Figure 2-11.

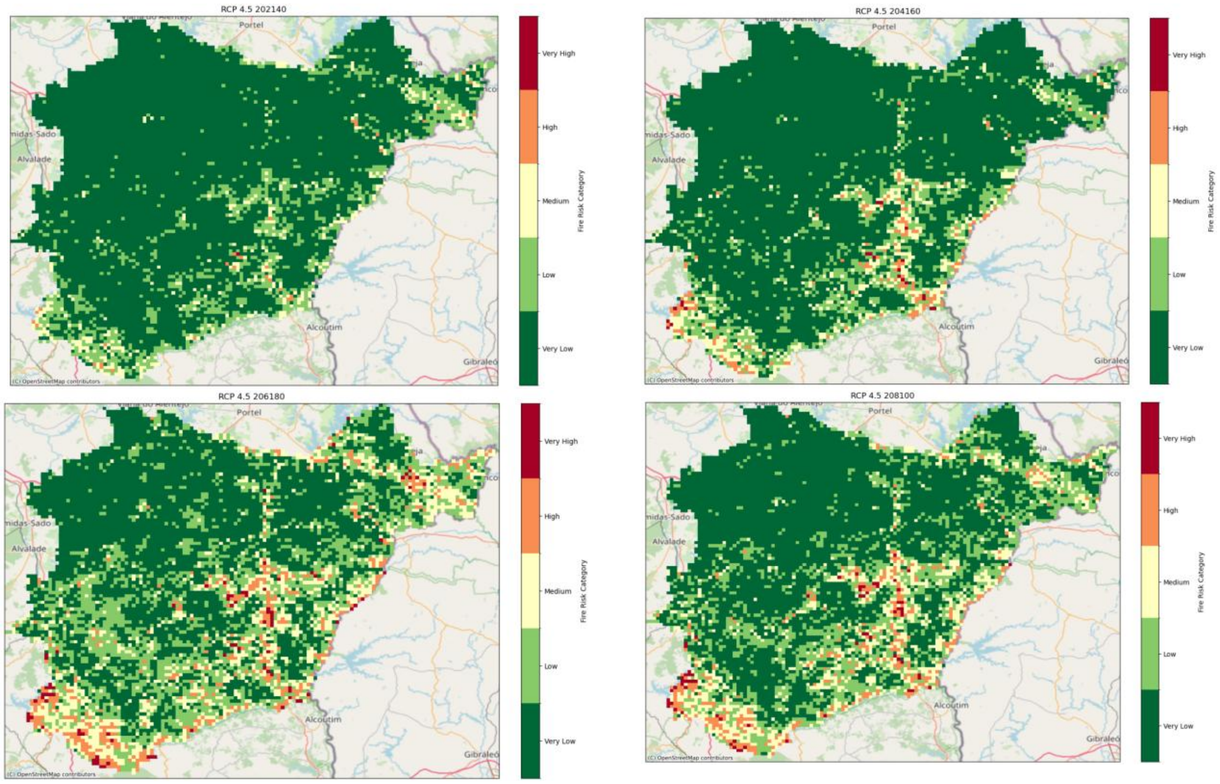

Figure 2-11 Risk of wildfire taking into consideration Terrestrial Water Points capacity.

The same routing approach is applied to fire stations and strategic parking areas, generating spatialized response-time estimates across Baixo Alentejo.

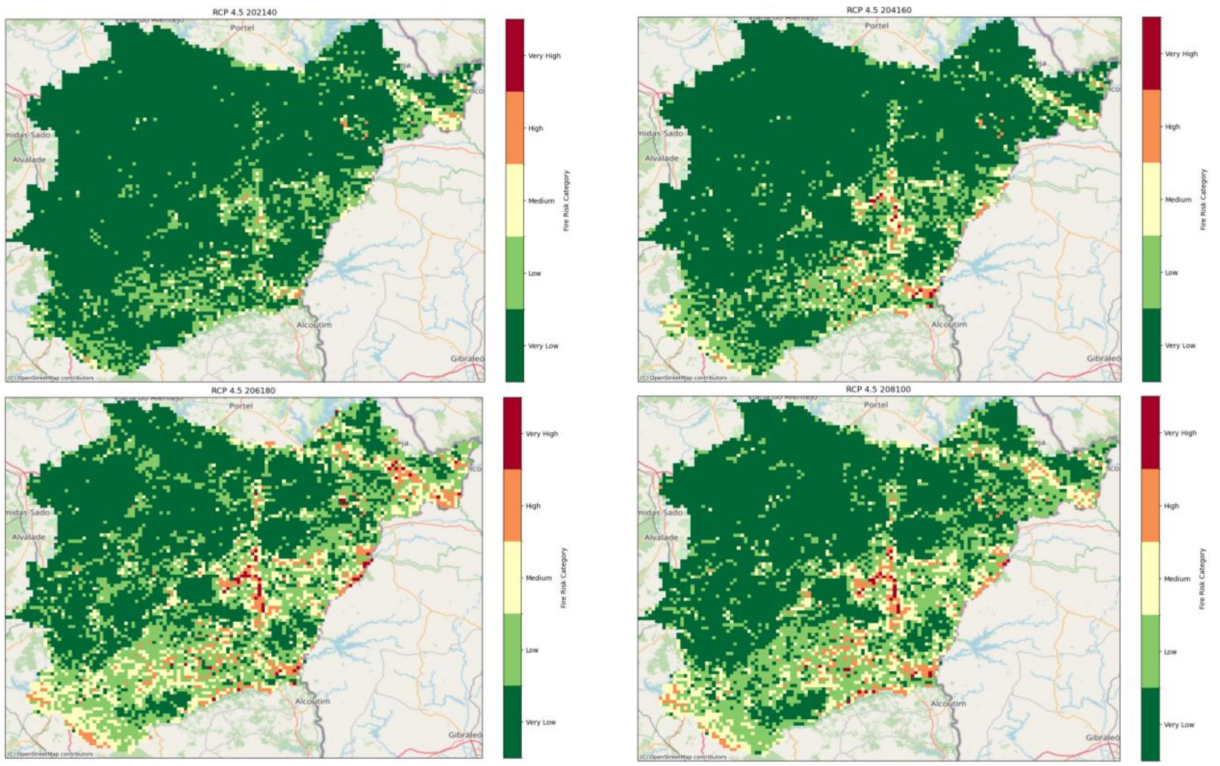

Figure 2-12 Risk of wildfire taking into consideration distance to Strategic Parking zones.

Taken together, the Phase 2 risk results indicate where projected hazard intensification coincides with exposed infrastructure and vulnerable receptors, and where operational response constraints may further exacerbate impacts. Although results should be interpreted primarily in a relative sense given dependence on dataset completeness and on the assumptions used to combine layers. The Phase 2 integration of an improved wildfire hazard model with expanded exposure and response-capacity information provides a more detailed and actionable basis for identifying priority areas for prevention, fuel management, and adaptation planning in Baixo Alentejo.

2.3.2 Hazard #2: Heatwaves - finetuning to local context

Table 2-3 Data overview workflow #2

Hazard data	*Vulnerability data*	*Exposure data*
Heat waves and cold spells in Europe **(Hooyberghs, et al. 2019)**	Vulnerable Population (WorldPop and Center for International Earth Sc 2018)	Land types (Direção-Geral do Território 2025)
Parishes - internal documentation of CIM	Urban areas - internal documentation of CIM	LST (Landsat 9 Collection 2 Level-2 data 2024)
	Lugares 2021 (Instituto Nacional de Estatística, I.P. 2024)	NDVI (Sentinel-2 MSI Level-2A data 2024)

2.3.2.1 Hazard assessment

The heatwave hazard assessment in Phase 2 maintains the same core climate indicator adopted in Phase 1 to ensure methodological continuity and comparability across project phases: the projected evolution in the frequency of heatwave days, defined using the EuroHEAT criterion as periods of three or more consecutive days in which daily maximum temperature exceeds the 90th percentile of the local historical distribution.

Hazard projections were derived from the Copernicus Climate Data Store dataset (Hooyberghs, et al. 2019), based on the EURO-CORDEX regional climate model ensemble for RCP 4.5 and RCP 8.5. The analysis evaluates two future horizons relative to the historical baseline 1986–2015: a near-future period (2016–2045) and a mid-century period (2046–2075). For each scenario and horizon, the annual number of heatwave days was calculated and expressed as a relative change (%) against the historical reference period.

To integrate these projections into the CLIMAAX risk framework and align outputs with local decision-making scales, relative changes were spatially aggregated to the level of civil parishes across Baixo Alentejo. The resulting hazard maps represent the climate-driven tendency for more frequent extreme-heat conditions at parish scale, independently of local exposure and vulnerability.

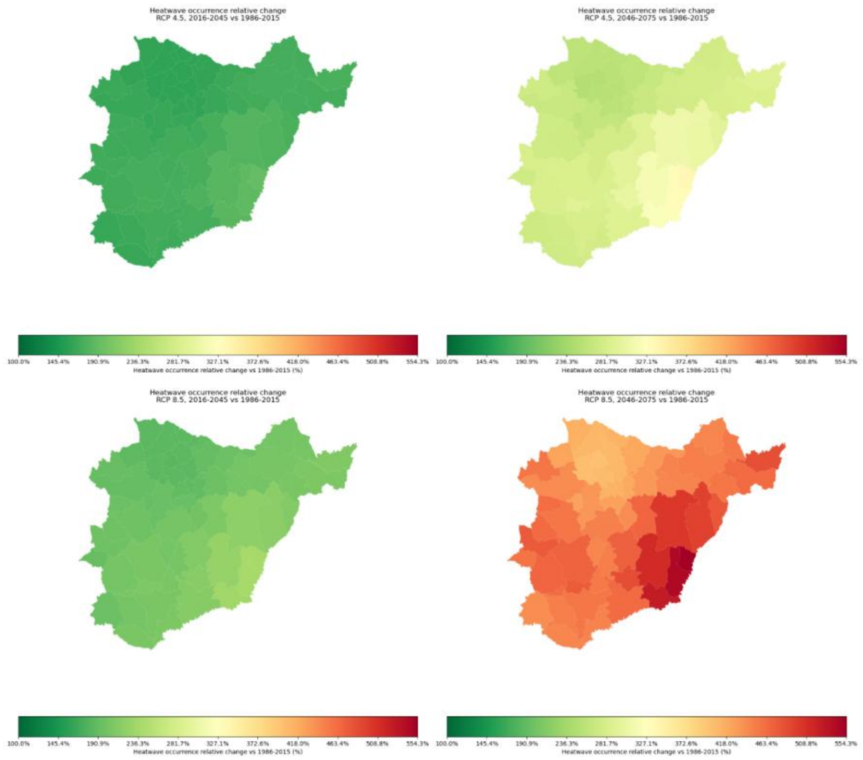

Figure 2-13 Heatwave occurrence relative change to 1986-2015 for scerarios 4.5 and 8.5 and periods 2016-2045 and 2046-2075.

Spatially, the strongest increases in heatwave days are consistently projected in the south-eastern sector of Baixo Alentejo, with relative changes reaching approximately +330% under RCP 4.5 and +500% under RCP 8.5. The remainder of the region also shows marked increases, though with a more spatially uniform pattern and weaker parish-to-parish contrasts. In Phase 2, high-resolution indicators related to urban form and land cover are not incorporated into the hazard definition; instead, they are used downstream to refine the understanding of micro-climatic amplification and exposure within built-up areas.

2.3.2.2 Risk assessment

At parish level, the heatwave hazard indicator from Section 2.3.2.1 (relative change in heatwave days) is combined with a vulnerability layer derived from population data. In line with the CLIMAAX urban heatwaves workflow, vulnerability is represented by the density of vulnerable population (people younger than 5 years or older than 65 years) in each parish, aggregated from gridded demographic data. The hazard and vulnerability layers are normalized and combined into composite indices, producing parish-scale risk maps consistent with the CLIMAAX methodology.

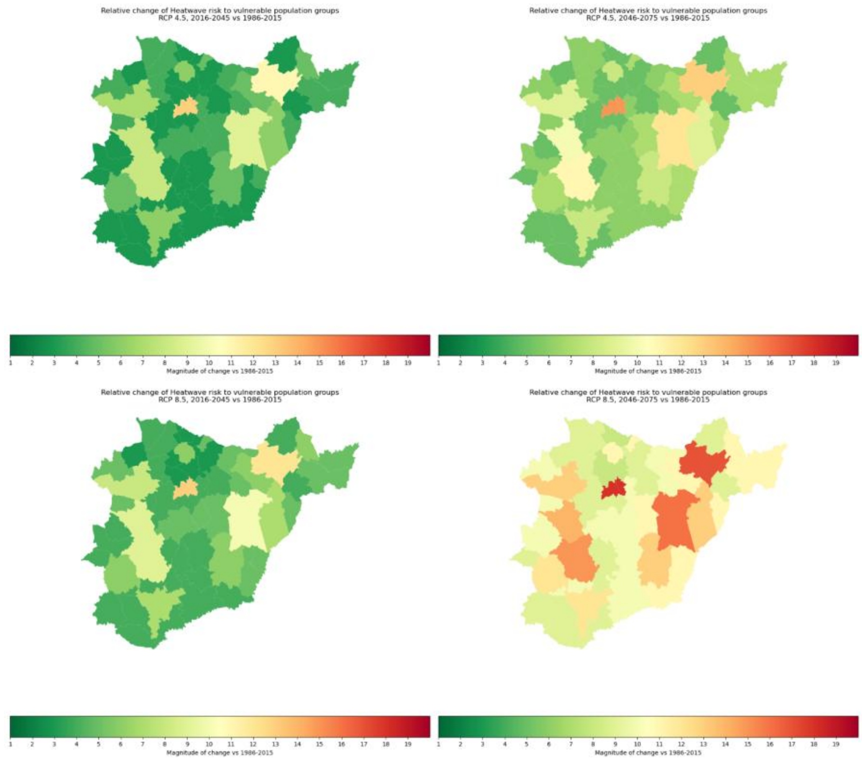

Figure 2-14 Relative change to Heatwave risk to vulnerable population for scenarios 4.5 and 8.5 and periods 2016-2045 and 2046-2075.

The parish-level screening highlights that the highest heatwave risk emerges where large projected increases in heatwave frequency overlap with high concentrations of vulnerable residents and ageing demographic profiles. In Baixo Alentejo, the risk to vulnerable populations is classified as very high in six civil parishes (Moura, Beja, Castro Verde, Aljustrel, Serpa, and Ferreira do Alentejo). This provides a clear first prioritization for targeted planning and preparedness; however, parish-scale outputs remain too coarse to resolve how risk is structured inside each municipality, particularly because parishes often combine urban cores with extensive rural land.To address this limitation, the EuroHEAT-based hazard indicator is re-analyzed specifically over the region's main built-up polygons, producing an urban-focused hazard metric that enables towns to be ranked according to expected increases in heatwave occurrence (Figure 2-15). This step supports a more decision-relevant framing, since heat-related impacts on people concentrate strongly in compact urban areas rather than across whole parish territories.

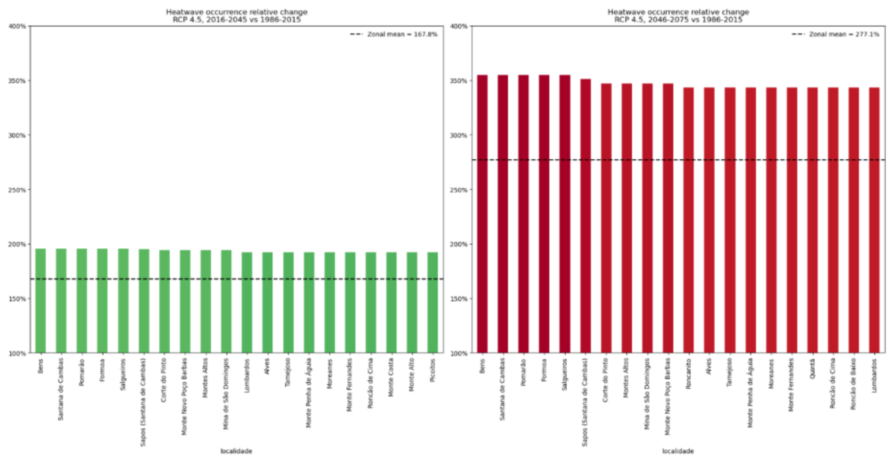

Figure 2-15 Heatwave occurrence relative change to 1986-2015 for scenarios 4.5 and 8.5 and periods 2016-2045 and 2046-2075 for 20 most affected urban areas.

Within selected urban areas, the climatic hazard signal is complemented by a high-resolution assessment of exposure using Land Surface Temperature (LST) and land-use information. Using Landsat-9 summer imagery, an LST raster is derived and intersected with detailed land-cover/land-use classes (e.g., compact residential fabric, more open residential areas, industrial and commercial zones). This makes it possible to compare temperature distributions across urban land types (Figure 2-16) and shows that dense residential blocks and industrial/commercial areas systematically occupy the warmest part of the LST distribution. These results refine the urban heat patterns identified in Phase 1 and indicate that, within each town, a relatively limited set of "grey" urban fabrics concentrates the highest potential exposure.

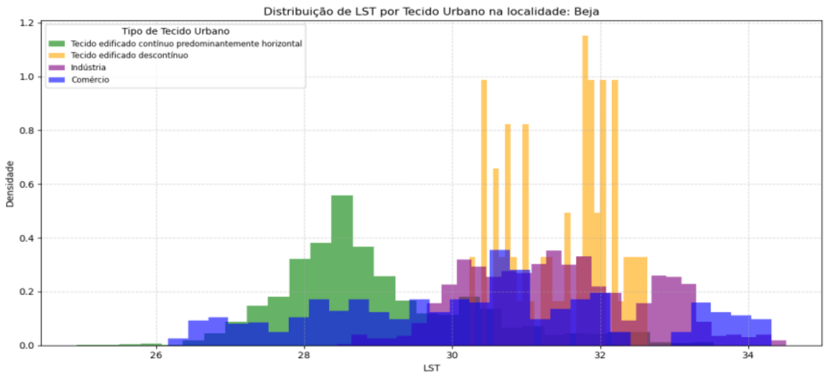

Figure 2-16 Land Surface Temperature distribution for each land type of urban areas.

The moderating influence of vegetation is examined through a joint analysis of LST and NDVI. An automatic classification (k-means) is applied to distinguish "green" pixels (vegetated surfaces such as parks, tree-lined streets, gardens, riparian corridors and agricultural plots) from "grey" pixels (buildings, paved areas and other non-vegetated surfaces). The classification is performed both across the full study area (resulting threshold: 0.365) and within urban masks (resulting threshold: 0.262) to focus on green infrastructure in and around towns. In both cases, temperature distributions show a consistent shift towards lower LST values in green pixels compared with grey ones. The examples of the resulting classification on the urban area of Beja are presented in Figure 2-17 and Figure 2-18.

Figure 2-17 Example of classification results for Beja using only the urban areas for the classification. (threshold: 0.262)

Figure 2-18 Example of classification results for Beja using all CIMBAL area for the classification. (threshold: 0.365)

In both cases, the comparison of temperature distributions (Figure 2-19) shows a clear shift towards lower LST values in green pixels compared with grey ones with the biggest difference using the threshold 0.365. The difference between the distributions was also quantifies using Earth Moving Distance that represents *on average, how far does a single unit of LST value need to move for one distribution to resemble the other* resulting on a value of 0.7287 for the case of using the classification method with only urban areas (threshold: 0.365) and a value of 1.2079 for the case of using all the CIMBAL region (threshold: 0.262).

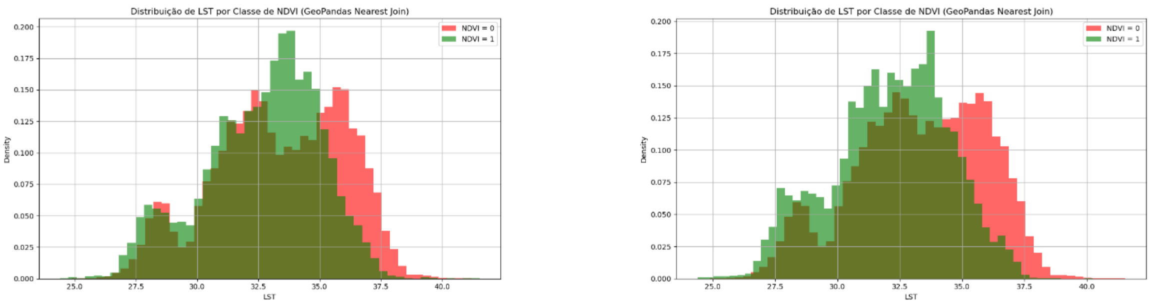

Figure 2-19 Distribution of Land Surface Temperatures for each class. Using the classification method with only urban areas (on the left) and using all the CIMBAL region (on the right).

Beyond the direct green–grey contrast, the analysis quantifies how far vegetation cooling extends into surrounding built-up areas. For each grey pixel, the distance to the nearest green pixel is calculated, and LST values are grouped into distance classes to evaluate how temperature changes with increasing separation from vegetated areas. Results indicate that grey pixels located near green areas are noticeably cooler than grey pixels that are more isolated, with a progressive weakening of the cooling effect as distance increases. In practical terms, parks, small gardens and tree-lined streets act as local cooling assets that reduce thermal exposure both within green areas and in the neighboring urban fabric. Although grey pixels are more numerous close to green areas, this difference in density is not directly reflected in the distance-based averages, since mean LST is computed per distance class. Analyzing the results we can see that grey pixels located next to green areas are noticeably cooler than grey pixels that are more isolated, and that the influence of vegetation can be detected up to ~150 m, with a gradual weakening of the cooling effect as distance increases. Moreover, when focusing only on denser vegetation (using a more restrictive NDVI threshold), the cooling signal persists to larger distances into grey areas. In practical terms, the mean LST for the region is reached within ~40 m when considering sparser vegetation, whereas with denser vegetation this "return to the regional mean" extends to ~50 m.

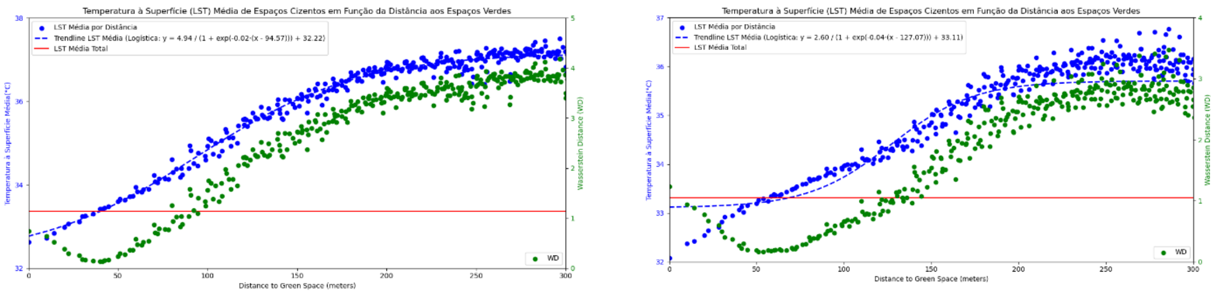

Figure 2-20 Average Land Surface Temperature for each distance for CIMBAL region, using threshold 0.262 (on the left) and threshold 0.365 (on the right).

Given that the central concern of heatwave risk is its impact on human health. However, data access constraints and limitations in the temporal coverage and consistency of diagnostic coding meant that robust statistical relationships between local temperature anomalies and health outcomes could not be derived. This difficulty is itself an important finding, as it reveals a gap in the monitoring and evaluation of heatwave impacts that would be valuable to address in future work.

Although it was not possible to directly link the Baixo Alentejo analysis with local hospital data, national evidence shows that heatwaves already have a measurable impact on mortality in Portugal. During a recent heatwave episode between 26-30 July, an excess of approximately 264 deaths was estimated for mainland Portugal (SIC Notícias 2025). Overall, mortality at national level was around 21.2% higher than expected, with the largest relative increase observed in the population aged 75 years and over (SIC Notícias 2025).

Recent studies for Portugal further show that hospital admissions increase by around 18.9% on heatwave days. The largest relative increase is observed for admissions due to burns (34.3%), highlighting the risks associated with prolonged sun exposure and direct contact with hot surfaces. (Associação Nacional dos Médicos de Saúde Pública (ANMSP) 2024)

Although heatwaves lead to statistically significant increases in hospital admissions across both sexes and all age groups, children are the most affected group, with an estimated 21.7% increase in admissions. Adults aged 18-64 years also show a substantial increase (19.7%). Among older people, admissions rise by around 17.2% (Associação Nacional dos Médicos de Saúde Pública (ANMSP) 2024); considered together with the higher heat-related mortality in this age group, this emphasizes the need to raise awareness of early signs of dehydration and decompensation, to provide climate-controlled spaces, to strengthen social support networks and to ensure easy access to transport for medical care.

2.3.3 Hazard #3: Agricultural Drought - finetuning to local context

Table 2-4 Data overview workflow #3

Hazard data	*Vulnerability data*	*Exposure data*
Available Water Capacity (AWC) (Hengl e Gupta 2019)	Productivity (kg/ha) - (Gabinete de Planeamento, Políticas e Administração Geral 2024)	MACAT (Direção-Geral do Território 2023)
DEM (Danielson e Gesch 2011)	Monetary Value (€/kg) - (Gabinete de Planeamento, Políticas e Administração Geral 2024)	Land types (Direção-Geral do Território 2025)
Wind speed (Copernicus Climate Change Service s.d.)		
Relative humidity (Copernicus Climate Change Service s.d.)		
Maximum temperature (Copernicus Climate Change Service s.d.)		
Mean precipitation (Copernicus Climate Change Service s.d.)		
Minimum temperature (Copernicus Climate Change Service s.d.)		
Surface solar radiation (Copernicus Climate Change Service s.d.)		
Crop coefficient (kc) - (Chapagain e Hoekstra 2004).		
length of growing period (LGP) - estimated from (Chapagain e Hoekstra 2004)		

Hazard data	*Vulnerability data*	*Exposure data*
Season start and end- (Chapagain e Hoekstra 2004)		
rooting depth (RD) (Allen, et al. 1998)		
depletion factor (DF) - (Allen, et al. 1998)		
crop water-yield response factor (ky) - (Doorenbos e Kassam 1979)		

2.3.3.1 Hazard assessment

Before assessing the agricultural drought hazard, a preliminary characterization of the main crop types in Baixo Alentejo was conducted to ensure that the analysis reflects the region's current agricultural profile (Figure 2-21). Crop distribution was identified using COS 2023 (permanent crops/land use) and MACAT 2023 (temporary crops suitability), and complemented with local reference productivity and price tables (GPP, 2024) to support subsequent impact quantification.

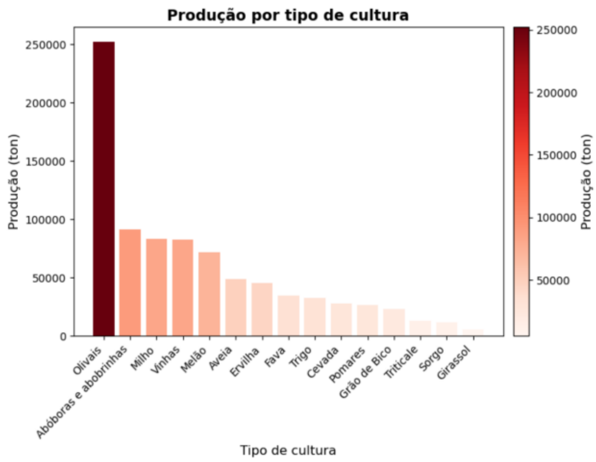

Figure 2-21 Production (ton) of each main culture of Baixo Alentejo.

The hazard component of agricultural drought was assessed using a combination of soil and climate indicators. First, historical Available Water Capacity (AWC) (Figure 2-22) was used to characterize baseline soil water retention potential and its spatial variability across the territory. This dataset highlights subregional heterogeneity in the capacity of soils to store water and sustain crops during dry periods; areas with lower AWC are more susceptible to rapid drought onset and higher stress in rainfed systems.

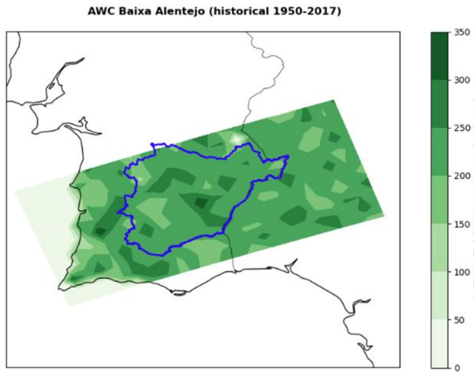

Figure 2-22 Historical Available Water Capacity for the NUTS2 region of Alentejo.

To complement the soil component, two climate-driven indicators were analyzed for the growing season: (i) cumulative precipitation and (ii) cumulative reference evapotranspiration (ET_0) (Figure 2-23), supporting an integrated view of water supply versus atmospheric demand. Yield loss under rainfed conditions was then estimated from the ETa/ETc relationship using CLIMAAX-aligned parameters.

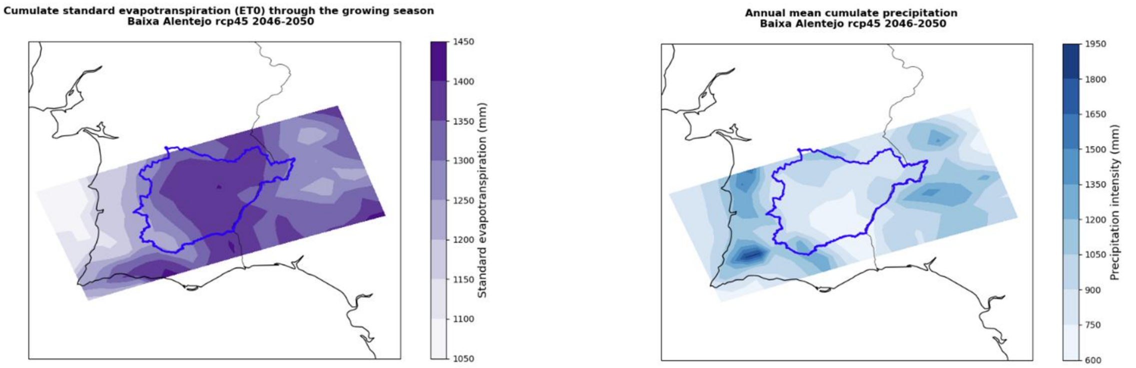

Figure 2-23 Projected cumulate precipitation intensity and standard evapotranspiration through the growing season.

Figure 2-24 present the projected yield loss (%) associated with precipitation deficits for the main crop groups mapped in Baixo Alentejo (e.g., olives, vineyards, maize, pumpkin/squash), under the selected scenario. While the spatial patterns differ by crop and local soil–climate conditions, the overall signal is consistent: increasing evapotranspiration demand combined with reduced precipitation during critical growth stages drives relevant yield penalties for several economically important crops.

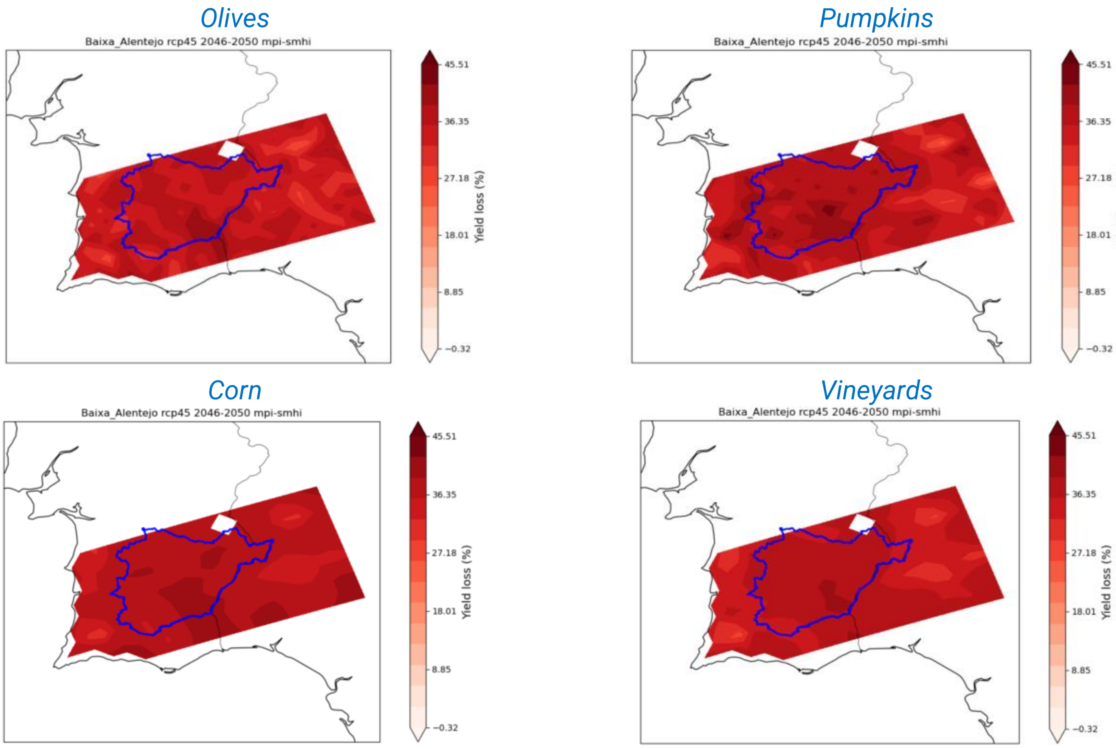

Figure 2-24 Yield Loss of the cultures with highest production.

In contrast, Figure 2-25 indicate comparatively lower projected yield losses for crops such as oats, wheat, barley, and fava. This lower loss signal should be interpreted primarily as a consequence of crop seasonality and exposure: these cool-season annual crops concentrate much of their growth during the wetter autumn–spring period, when precipitation is typically higher and evaporative demand lower in Mediterranean climates. Under the CLIMAAX rainfed precipitation-deficit/ETa–ETc formulation, this alignment generally reduces the intensity and duration of simulated water stress. Importantly, lower projected yield loss does not necessarily imply greater drought resistance; it may also reflect shorter overlap with peak summer dryness, differences in crop coefficients and phenology, and the fact that irrigation dynamics and local management practices are not explicitly represented in the current hazard calculation.

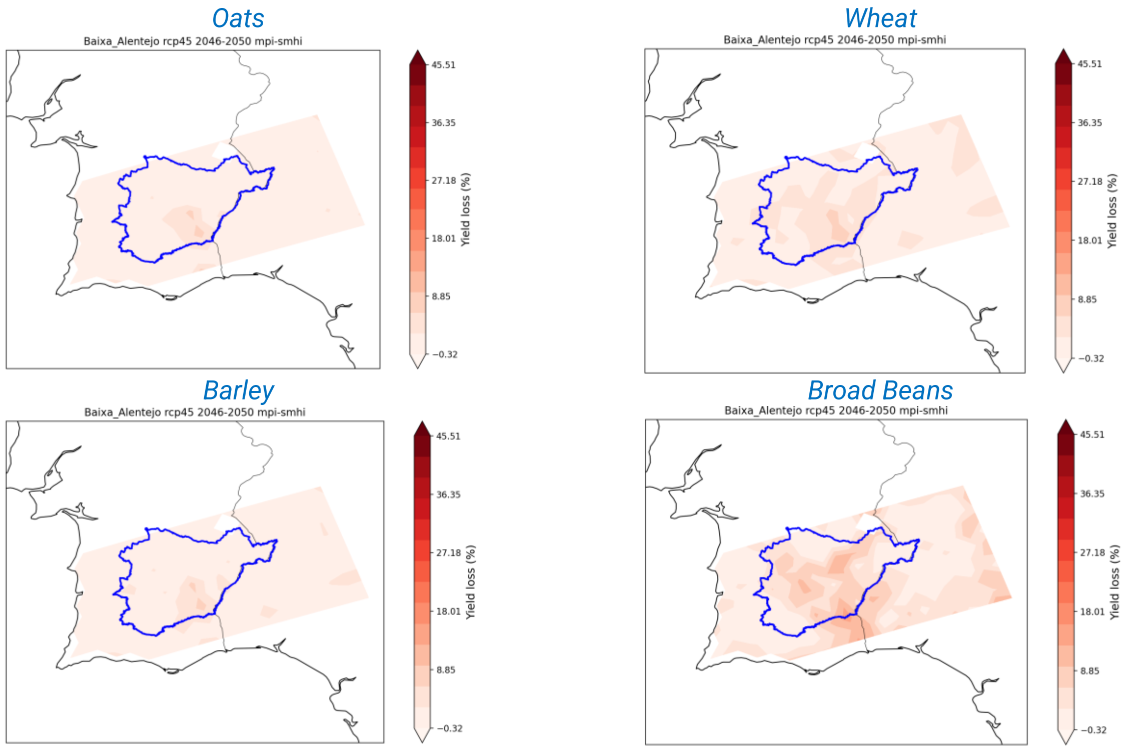

Figure 2-25 Yield loss of least-affected crops.

Comparing yield-loss patterns for olives, vineyards, maize, and pumpkin/squash with those for oats, wheat, barley, and fava; the latter group is largely composed of cool-season annual crops, whose peak growth and water demand typically occur during the wetter part of the Mediterranean rainfall regime (autumn–spring). In the CLIMAAX precipitation-deficit/ETa–ETc formulation, this seasonal alignment tends to reduce modelled water-stress intensity and therefore produces comparatively lower yield losses. By contrast, maize and pumpkin/squash have higher crop water demand during mid-season and can extend further into the dry season; under rainfed assumptions, they are therefore more sensitive to precipitation deficits. For perennial crops (olives and vineyards), drought tolerance supports plant survival, but productivity can still decline substantially because water stress during key stages (e.g., flowering, fruit set, and fruit development) reduces yield. Finally, where irrigation is present (notably influenced by the Alqueva system), losses for summer crops may be overestimated unless irrigation supply and allocation constraints are explicitly represented.

2.3.3.2 Risk assessment

To estimate the potential economic impacts of agricultural drought, projected yield reductions were converted into monetary loss (€/ha) using locally referenced productivity (kg/ha) and price (€/kg) values (GPP, 2024). This adaptation represents a key improvement over a purely global-database approach, enabling an impact metric that is more interpretable for regional stakeholders and planning processes.

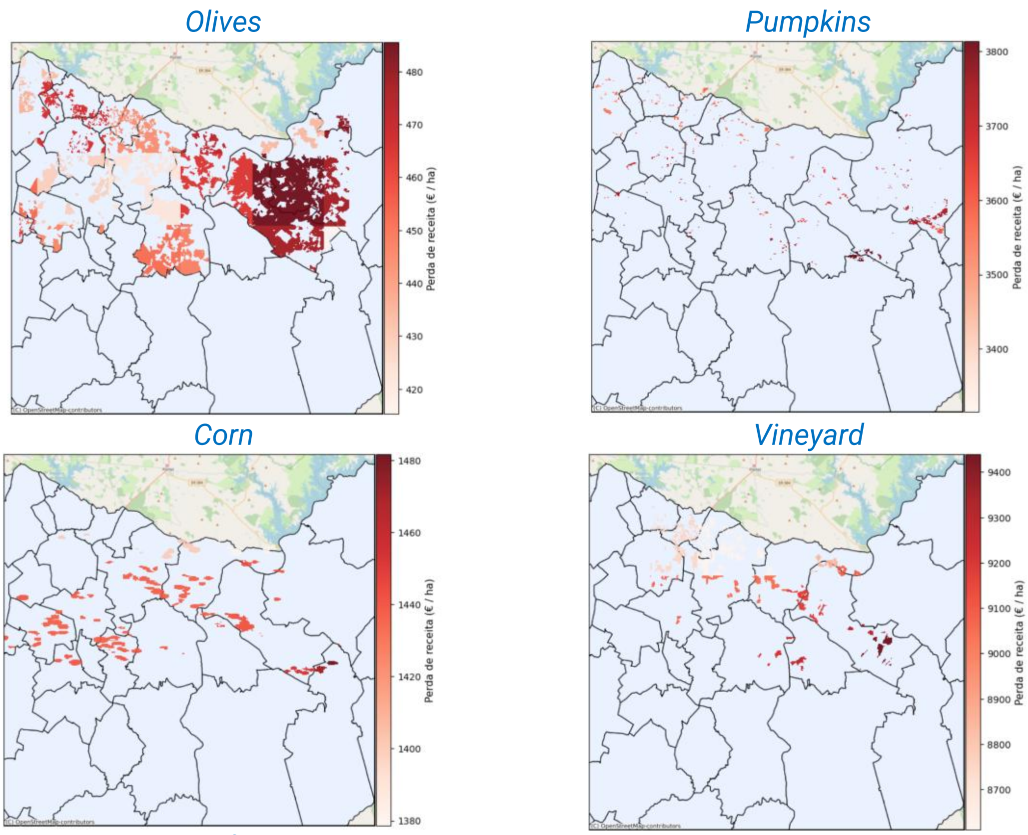

Figure 2-26 Monetary Loss of the cultures with most production in Baixo Alentejo.

Figure 2-26 summarize the resulting projected losses for the main Baixo Alentejo crop types included in this regionalized analysis. These estimates are useful for understanding relative spatial patterns and the order of magnitude of impacts, but they should not be treated as ground truth due to three important limitations:

1. Spatial granularity and local calibration: improving confidence would require higher-resolution precipitation projections and AWC (or comparable soil water storage indicators) calibrated for the region's agricultural zones.
2. Irrigation representation: the influence of irrigated areas (notably linked to the Alqueva system) is not yet explicitly integrated into the current drought-loss calculation.
3. Operational water constraints under drought: even where irrigation exists, drought conditions can reduce available water and tighten distribution rules, meaning irrigation cannot be assumed as a full mitigation measure under increasing drought frequency and severity.

2.4 Key Risk Assessment Findings

2.4.1 Mode of engagement for participation

Risk evaluation was conducted through an iterative stakeholder engagement process designed to validate relevance, interpretability, and decision usefulness of the Phase 2 outputs. The process built on:

1. *a regional workshop focused on introducing the CLIMAAX approach, presenting Phase 1 screening results, and prioritising Phase 2 "lines of analysis" through a structured scoring exercise; and*
2. *a Phase 2 workshop focused on reviewing the selected analyses, presenting intermediate methods/results, and discussing implications and next steps toward adaptation planning.*

Feedback gathered during Phase 2 reinforced the need to: (i) increase the representativeness of local land-use and crop systems in drought analyses, (ii) strengthen operational relevance for wildfire planning by reflecting response constraints (accessibility and water points), and (iii) complement climate indicators for heatwaves with local exposure and mitigation diagnostics inside urban areas.

2.4.2 Gather output from Risk Analysis step

Risk evaluation used the complete set of outputs generated in the Phase 2 Risk Analysis for the three priority hazards, including all hazard, exposure, vulnerability, and composite risk maps/indices, as well as the additional operational and impact indicators developed in Phase 2 (e.g., response-capacity proxies for wildfires, remote-sensing diagnostics for heat, and crop-specific yield and monetary loss metrics for drought). All these results were compiled and used in the evaluation dashboard to support the scoring of severity, urgency, and resilience capacity.

2.4.3 Assess Severity

Severity was assessed for current and future conditions using a combination of: observed regional sensitivity (hot summers, low summer precipitation), the Phase 2 modelled hazard and risk outputs, and stakeholder perspectives on impacts, critical receptors, and cascading effects.

- **Heatwaves — severity: substantial to critical.** Heatwaves represent a direct health risk and a compounding driver of other risks (notably agriculture drought). Phase 2 outputs indicate strong increases in heatwave-day occurrence across the region, with high-risk concentrations where projected hazard increase coincides with vulnerable population densities. Potential cascading effects include increased morbidity and mortality, reduced labour productivity in outdoor work, and stress on local services during peak events. Based on the combination of high hazard intensification and high sensitivity of exposed groups, heatwave severity is assessed as historically **substantial** and **critical** in the future due to its increasing trend.

- **Agricultural drought — severity: moderate to substantial.** Drought is a recurrent and structurally important risk for Baixo Alentejo due to reliance on climate-sensitive agricultural and agroforestry systems and increasing water stress. Phase 2 results show crop-dependent yield penalties and economically meaningful losses when translated into monetary metrics. Indirect impacts include pressure on farm income stability, long-term viability of certain crop choices under rainfed conditions, and heightened competition for water resources. Given the breadth of affected sectors and the potential for persistent productivity decline, severity is assessed as **moderate**, with the potential to reach **substantial** where drought coincides with constrained water availability and high socio-economic dependence.

- **Rural wildfires — severity: moderate to substantial.** Although historical fire-event density is lower in parts of the territory than in other Portuguese regions, wildfire hazard and risk are expected to increase, particularly under more adverse scenarios with areas such as the southwest region that have a lot of potential for wildfire occurrence. Phase 2 risk overlays show that impacts are receptor-dependent: ecological and land-management consequences may be high even where population exposure is lower, while infrastructure impacts concentrate where hazard overlaps critical networks and services. Considering the potential for ecosystem damage, high-cost suppression operations, and disruption to mobility and services, wildfire severity is assessed as **moderate** to **substantial**.

Stakeholder perspectives contributed primarily by highlighting where model outputs align with operational experience (e.g., areas with constrained access or limited suppression resources) and by stressing the importance of translating maps into decision-relevant categories and triggers.

2.4.4 Assess Urgency

Urgency was assessed considering projected change from current to future risk, the timing of expected impacts, the persistence of underlying drivers, and the balance between slow-onset trends and event-based escalation.

- **Heatwaves — urgency: immediate action needed.** Heatwaves are already occurring and are projected to intensify markedly in the near-future horizon. The hazard is event-based (acute episodes), but its frequency increase is driven by a persistent warming trend, implying rising baseline stress and repeated exceedance of critical thresholds. Given the health implications and the feasibility of preparedness interventions (communication, cooling spaces, urban greening and shading measures), urgency is assessed as **immediate action needed**.

- **Agricultural drought — urgency: more action needed.** Agricultural drought reflects slow-onset climatic drivers (reduced precipitation effectiveness and higher evapotranspiration demand) combined with recurring seasonal stress. The risk is already material for agricultural productivity and water management, and future projections reinforce persistence and intensification. A few adaptations were already put in place by optimizaing the watter usage for irrigation and by doing efforts in transitioning for winter cultures but because some responses require multi-year planning (crop adaptation, water-efficiency investment, allocation planning), urgency is assessed as **more action needed**.

- **Rural wildfires — urgency: more action needed.** Wildfire risk is strongly seasonal and event-driven, but increases are reinforced by persistent warming and drought conditions. Phase 2 outputs support the prioritizations of preparedness and prevention in areas of increasing hazard, particularly where response capacity is constrained. Given the potential for high-impact seasons and the value of pre-season measures (fuel management, access planning, water-point strategy), urgency is assessed as **more action needed**, with targeted “immediate” actions justified in hotspots.

2.4.5 Understand Resilience Capacity

Resilience capacity was assessed considering existing plans and measures, institutional coordination, technical capacity, available resources, and known weak spots across financial, human, physical, natural, and social dimensions.

Overall, Baixo Alentejo benefits from an established planning basis through the intermunicipal adaptation framework (PIAAC-BA) and municipal-level plans, and from collaboration with key regional actors responsible for water, forestry, and civil protection. This provides a foundation of **medium to substantial** capacity, but with uneven implementation readiness and technical constraints that limit operational use of risk information.

- **Heatwaves — resilience capacity: medium.** Strengths include the ability to implement low-regret preparedness measures and to integrate heat-risk considerations into municipal services and urban planning. Weak spots include limited availability of locally consolidated heat-health impact datasets, challenges in identifying and supporting socially isolated individuals, and the need for more systematic local triggers for action (e.g., thresholds for warnings, activation of cooling shelters).

- **Agricultural drought — resilience capacity: substantial.** Strengths include the presence of a major water infrastructure and a policy framework for water efficiency and agricultural planning. Weak spots include reliance on climate-sensitive income sources, incomplete representation of irrigated versus rainfed systems in current impact estimates (which affects targeting), and uncertainty about future water allocation constraints under compound drought conditions.
- **Rural wildfires — resilience capacity: low.** Strengths include established national and regional civil protection and forestry structures. The Phase 2 analysis highlights operational constraints: areas with limited accessibility and/or sparse water-point coverage represent capacity weak spots even when institutions are present and resource availability is generally speaking scarce.

2.4.6 Decide on Risk Priority

Risk priority was assigned by combining the three evaluation dimensions—severity, urgency, and resilience capacity—using the evaluation dashboard logic and stakeholder-informed interpretation of the Phase 2 outputs.

Priority-setting followed these principles: risks assessed as critical/substantial in severity and immediate/more action needed in urgency were prioritized first, particularly where resilience capacity is medium or low; receptor-specific considerations were retained (e.g., health impacts for heatwaves, economic impacts for drought, operational response constraints for wildfires); and priorities were framed to support Phase 3 translation into feasible adaptation measures and monitoring triggers.

Based on the Phase 2 evidence and stakeholder discussions to date, the preliminary prioritization is:

- **Very High priority: Heatwaves**, due to strong current relevance, clear future intensification, and broad socio-economic and health implications.
- **High but targeted priority: Rural wildfires**, prioritized particularly in areas where increasing hazard coincides with constrained response capacity and/or critical receptors (infrastructure, high-value ecosystems).
- **High priority: Agricultural drought**, also due to strong current relevance, clear future intensification, and broad socio-economic implications.

Final confirmation of priority classes—including explicit thresholds for “tolerable” versus “non-tolerable” risk and the operational triggers to act—will be consolidated in Phase 3 through structured stakeholder sessions using the dashboard as a shared reference.

A	B	C	D	E	F
Risk Workflow	Severity		Urgency	Capacity	Risk Priority
	C	F		Resilience/ CRM	
River flooding					
Coastal flooding					
Heavy rainfall					
Heatwaves					Very High
Drought					High
Fire					High
Snow					
Wind					

Severity	Urgency	Resilience Capacity	Risk Ranking
Critical	Immediate action needed	High	Very high
Substantial	More action needed	Substantial	High
Moderate	Watching brief	Medium	Moderate
Limited	No action needed	Low	Low

Figure 2-27 Key Risk Assessment.

2.5 Monitoring and Evaluation

Phase 2 strengthened the technical robustness and local relevance of the climate risk assessment by replacing key Phase 1 "best-available" European/global proxies with regional datasets and by extending the analysis beyond the standard workflow outputs. Compared to Phase 1, the main learning is that model performance and decision usefulness improve substantially once the input data reflects the real land-use, crop systems, and infrastructure constraints of Baixo Alentejo.

The main technical bottlenecks in Phase 2 were: (a) aligning heterogeneous local datasets (different spatial resolutions, classification systems, and update cycles), (b) ensuring that "extra" indicators (e.g., vegetation–temperature relationships, water-point coverage) remain consistent with CLIMAAX concepts of hazard, exposure, and vulnerability, and (c) improving wildfire model sensitivity while maintaining physical interpretability of climate drivers. These were addressed by (i) explicitly documenting data sources and methodological adaptations in the regionalized workflows, and (ii) updating the wildfire modelling approach to a Portugal-wide training domain with a revised algorithm and constraints designed to better reflect climatic change signals in hazard outputs.

Stakeholders played a central role in guiding Phase 2 priorities by scoring and selecting the specific "lines of analysis" to be developed for agricultural drought and rural wildfires, ensuring that the second-phase work focused on information needs perceived as most relevant and feasible given data availability. This prioritization step helped narrow the assessment to outputs that can support operational planning (e.g., identifying resilient sub-regions; analyzing constraints for wildfire response linked to accessibility and water points).

Feedback at this stage is primarily reflected in what was prioritized and implemented analytically; deeper validation of results (e.g., thresholds for "acceptable" risk levels, locally agreed classification cut-offs) remains a key item to consolidate through the next engagement steps.

Learning is ensured through the project's iterative structure: Phase 2 directly targeted known Phase 1 limitations (notably crop representativeness and wildfire model performance) and translated workshop prioritization into concrete methodological refinements. The workflow-based approach also supports repeatability and future recalculation as new climate runs, socio-economic data, or land-use layers become available.

Phase 2 integrated local datasets for agricultural drought (regional crop/land-use mapping and local reference values for productivity and prices) and expanded heatwave analyses using remote sensing indicators (vegetation and land surface temperature) to better characterize urban heat mitigation effects.

Remaining needs to further improve confidence and policy relevance include: (i) explicit representation of irrigated vs. rainfed systems in drought impact calculations (a method is under development), (ii) additional locally validated vulnerability layers (e.g., sectoral workforce exposure, health-system sensitivity indicators, social isolation), and (iii) stakeholder-agreed classification rules for certain derived indices currently based on automatic thresholds.

Final outcomes will be communicated through (i) stakeholder-facing synthesis material (maps and rankings targeted to municipal and sectoral responsibilities), (ii) continued workshops to validate assumptions and prioritize feasible adaptation options, and (iii) public sharing of deliverables and supporting outputs through the project repository, consistent with CLIMAAX reporting requirements.

Phase 2 outputs provide a basis for defining a monitoring framework for the three priority risks (agricultural drought, heatwaves, rural wildfires) by establishing baseline spatial risk patterns and locally meaningful metrics (e.g., €/ha drought losses, exposure hotspots, response-capacity proxies). However, a consolidated operational monitoring system (indicators, update frequency, institutional ownership, and decision triggers) should be formalized in Phase 3 so that CRA outputs can be linked to adaptation planning cycles and to routine updates of datasets and assumptions.

Phase 2's efficiency gains came from focusing effort on stakeholder-prioritized extensions and on a limited set of high-impact methodological upgrades (local crop economics; Portugal-wide wildfire recalibration; remote sensing heat indicators), rather than broadly expanding scope. The main trade-off is that some components (notably irrigation representation in drought impacts and formalized threshold-setting for certain indices) require additional development and stakeholder agreement before they can be used as monitoring triggers in practice.

Overall, Phase 2 materially improved risk understanding by (i) increasing representativeness of agricultural drought impacts for Baixo Alentejo, (ii) enhancing interpretability of heatwave-related exposure and mitigation factors, and (iii) strengthening wildfire hazard modelling and response-capacity perspectives via new, locally actionable indicators. This provides a clearer technical foundation for Phase 3, where the emphasis shifts to selecting and prioritizing adaptation measures aligned with the validated risk picture.

2.6 Work plan Phase 3

Phase 3 represents the transition from climate risk assessment to action-oriented planning, consolidating the analytical outputs generated during Phases 1 and 2 into a coherent set of strategic responses for the Baixo Alentejo region. Building upon the identification, prioritization and refinement of climate risks and vulnerabilities — with particular emphasis on heatwaves and wildfires — this phase will focus on the systematic exploration, assessment and structuring of climate adaptation and mitigation options that are both territorially grounded and policy-relevant.

In line with the CLIMAAX framework, Phase 3 will operationalize the final steps of the risk management cycle, namely the translation of key risk insights into actionable strategies and the reinforcement of monitoring, evaluation and governance mechanisms. The work will explicitly leverage the quantitative and qualitative evidence produced in the previous phases, ensuring continuity between risk analysis, vulnerability assessment and response design.

The activities foreseen for Phase 3 will start with a comprehensive review and consolidation of the refined climate risk assessments developed in Phase 2. This process will ensure that the prioritization of actions is directly informed by the severity, urgency and adaptive capacity dimensions previously analyzed. Particular attention will be given to the spatial differentiation of risks and vulnerabilities across the territory, allowing the identification of context-specific intervention pathways and avoiding one-size-fits-all solutions.

Based on this consolidated risk baseline, Phase 3 will focus on the identification and structuring of a portfolio of adaptation measures aimed at reducing exposure and vulnerability to climate hazards. These measures will encompass structural, nature-based and governance-oriented solutions, addressing both short-term coping needs and longer-term resilience building. At the same time, and in response to stakeholder feedback, mitigation dimensions will be explicitly considered, particularly where synergies with adaptation can be achieved, such as through land-use planning, ecosystem restoration, energy efficiency, or sustainable resource management practices.

The selection and prioritization of adaptation and mitigation options will be guided by criteria of feasibility, effectiveness, cost-efficiency and institutional compatibility, ensuring alignment with existing regional and local planning instruments, including the Intermunicipal Climate Change Adaptation Plan (PIAAC). This process will support the integration of climate considerations into ongoing policy frameworks and decision-making processes, reinforcing the mainstreaming of climate resilience across sectors.

Stakeholder engagement will play a central role throughout Phase 3. Targeted participatory activities will be organized to validate findings, refine priorities and incorporate local knowledge into the design of proposed actions. These interactions will also contribute to strengthening risk ownership, institutional coordination and collective capacity to implement and sustain climate responses over time. The engagement process will be structured to ensure representativeness across relevant sectors and administrative levels, fostering shared understanding and commitment.

The outputs of Phase 3 will include a structured set of climate adaptation and mitigation strategies, accompanied by implementation-oriented guidance outlining responsibilities, potential timelines and monitoring considerations. These outputs will be designed to support both immediate decision-making needs and longer-term strategic planning, providing a robust basis for enhancing climate resilience in the Baixo Alentejo.

Overall, Phase 3 will consolidate the CLIMAAX approach at regional level by closing the loop between climate risk assessment and action, ensuring that scientific evidence, stakeholder perspectives and policy objectives converge into a coherent and implementable response framework.

3 Conclusions Phase 2- Climate risk assessment

Phase 2 of the CLIMAAX Baixo Alentejo climate risk assessment consolidated and regionalised the Phase 1 findings by integrating local datasets, refining modelling choices, and producing additional indicators that better reflect how climate hazards translate into impacts and operational constraints in the territory. Building on the Phase 1 conclusion that agricultural droughts, heatwaves, and rural wildfires are the region's priority climate risks, Phase 2 focused on improving fitness-for-purpose: ensuring that the assessment outputs can be interpreted by regional and municipal stakeholders and can serve as a credible basis for adaptation planning in the final project phase.

A first key conclusion is that the value of a CRA in Baixo Alentejo depends strongly on whether the assessment reflects the region's real production systems and land-use patterns. Phase 1 highlighted a major limitation in the agricultural drought workflow: the mismatch between CLIMAAX default crop datasets and the crops that structure the regional economy. Phase 2 addressed this by introducing local crop and land-use information and by adapting the drought-impact calculation to incorporate local reference values for productivity and crop prices, enabling impact expressions that are more directly usable (e.g., monetary loss per hectare) for planning and prioritization. This substantially increases the interpretability of drought risk patterns, while also making remaining methodological gaps explicit—particularly the need to represent irrigation, which is critical in parts of the region and is still being developed for inclusion in future iterations.

A second key conclusion is that heatwave risks understanding benefits from combining climate indicators with place-based exposure and mitigation diagnostics. Phase 2 retained the core logic of analyzing extreme heat occurrence but expanded the assessment with remote sensing-based analyses that quantify how vegetation presence and land-use classes relate to land surface temperature patterns, and by identifying the most exposed population agglomerations. These extensions strengthen the practical relevance of the heatwave assessment by connecting the hazard signal to actionable urban and peri-urban planning levers (e.g., protecting the most exposed settlements and identifying where nature-based cooling potential is most relevant).

A third key conclusion concerns rural wildfires: Phase 2 demonstrates that improving hazard modelling in data-scarce contexts requires both scale and interpretability. Phase 1 documented limited model performance for Baixo Alentejo due to low historical fire-event density and class imbalance. In Phase 2, wildfire modelling was updated by training on a broader Portugal-wide domain and by applying a revised modelling strategy designed to better reflect expected climatic influences on wildfire susceptibility. In parallel, Phase 2 added analyses aimed at operational constraints, including metrics related to the territorial coverage of water points and the accessibility of high-danger areas—elements that directly affect preparedness and response planning.

Across the three hazards, stakeholder participation in Phase 2 mainly shaped prioritization and scope: stakeholders reviewed and scored proposed lines of analysis for drought and wildfires, ensuring that the work program concentrated on questions perceived as most relevant and feasible (given local data availability). This engagement step strengthens risk ownership and increases the likelihood that the CRA outputs will be used, because the second-phase analytical deepening was explicitly aligned with stakeholder-defined needs.

Despite substantial progress, Phase 2 also clarifies what was not yet fully addressed. The most important remaining challenges include: (i) completing and validating a robust method to incorporate irrigation into drought-impact estimation; (ii) further enriching vulnerability representation for heatwaves beyond demographic proxies, where possible, to better capture health-system and socio-economic sensitivity; and (iii) formalizing classification thresholds and decision-relevant risk categories with stakeholders for derived indices currently based on automatic thresholding. These are typical requirements of moving from a regionalized assessment to an operational tool used to trigger and prioritize adaptation actions.

In conclusion, Phase 2 delivers a more locally grounded, more interpretable, and more decision-relevant climate risk assessment for Baixo Alentejo than Phase 1, while keeping full alignment with CLIMAAX reporting logic and workflow transparency. The assessment confirms the continued priority of agricultural drought, heatwaves, and rural wildfires, and provides improved evidence on where risk concentrates and which mechanisms are most important for impacts and response constraints. This strengthened evidence base sets up Phase 3 to focus on the translation of risk insights into a prioritized set of adaptation measures, validated with stakeholders and aligned with regional and municipal planning instruments.

4 Progress evaluation

Table 4-1 Overview key performance indicators

Key performance indicators	*Progress*
Submission of all 5 deliverables	2/5 (40%)
At least 2 different workflows applied successfully during phase 1	3/2 (100%)
6 different events involving the stakeholders	2/6 (33%)

5 Supporting documentation

Workflow #1 – Wildfires

Filename: Wildfires.zip

Includes maps, raster images and visualizations related to the wildfire workflow, under RCP 4.5 and 8.5 for four time periods, a short-term, a medium-term and a long-term future periods. Also includes the code related to this workflow.

Workflow #2 – Heatwaves

Filename: Heatwaves.zip

Includes hazard and vulnerability maps produced in the heatwave workflow, under RCP 4.5 and RCP 8.5 for two time periods, one short-term and another long-term future periods. Also includes the code related to this workflow.

Workflow #3 – Agricultural Drought

Filename: Agricultural-Drought.zip

Includes hazard and vulnerability maps produced in the heatwave workflow, under RCP 4.5 and RCP 8.5 for five time periods, from 2026 to 2050. Also includes the code related to this workflow.

All outputs listed above have been uploaded to the Zenodo repository under the CLIMAAX entry for Baixo Alentejo:

Zenodo Repository Link: https://doi.org/10.5281/zenodo.18281346

DOI: 10.5281/zenodo.18281346

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