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D2.3 - Quantitative and Qualitative Assessments of Societal and Human Aspects of Vulnerabilities

WP2 - Task 2.3
December 2025

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Summary

This deliverable, D2.3: Quantitative and Qualitative Assessments of Societal and Human Aspects of Vulnerabilities, provides a comprehensive evaluation of climate risk across Europe, moving beyond traditional biophysical and economic modeling to rigorously integrate human and social dimensions. Synthesizing results from eight sectoral Climate Change Hotspots (CCHs) and event-based Storylines (STLs), the report employs a framework to link physical hazards—such as heatwaves, storms, and floods—to concrete constraints on individual and communal well-being. D2.3 establishes a robust, evidence-based foundation for prioritizing adaptation investments where the societal burden is highest, ensuring that future climate-resilient pathways in Europe are both effective and socially equitable.

Keywords

Socio-economic vulnerability (SEV), Social impacts, Capability Approach, Human well-being, Climate adaptation policy, Socio-Economic Resilience, Blue-Green Infrastructure (BGI), Multi-Hazard Risk Assessment, Social Inclusion, Nature-Based Solutions (NBS)

Abbreviations and acronyms

Acronym	Description
BGI	Blue-Green Infrastructure
CA	Capability Approach
CICES	Common International Classification of Ecosystem Services
CCH	Climate Change Hotspot
CSA	Case Study Areas
DSS	Decision Support System
EAD	Expected Annual Damage
ES	Ecosystem Services
GDP	Gross Domestic Product
HPP	Heat Prevention Plan
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
M&A	Mitigation and Adaptation
NBS	Nature-Based Solutions
NUTS	Nomenclature of Territorial Units for Statistics (levels 2 and 3)
RCP	Representative Concentration Pathway
ROS	Rain-on-Snow (events)
SE	Socio-Economic
SSP	Shared Socio-economic Pathway
STLs	Story-Lines
SVI	Social Vulnerability Index
WP	Work Package

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1. Introduction

This Deliverable, D2.3: Quantitative and Qualitative Assessments of Societal and Human Aspects of Vulnerabilities, synthesizes the results from the analysis of sectoral Climate Change Hotspots (CCHs) and event-based Storylines (STLs) under Work Package 2.

1.1. Purpose and Scope

The purpose of D2.3 is to provide a comprehensive assessment that captures the full spectrum of climate extreme event impacts. The 8 case studies integrate existing high-resolution climate knowledge, event-based observations on experienced sectoral impacts, and Socio-Economic (SE) perspectives derived from adaptation priorities. These case studies cover all European regions and relevant SE sectors through the integrated analysis of the observed (present) and modelled (potential) impacts of climate extreme events on the SE risks. The analysis is applied for case studies at the regional level and is based on quantitative and qualitative methods, including, but not limited to, climate and ecosystem linked modelling, SE modelling, quantitative and qualitative assessments of societal and human aspects of vulnerabilities, and synthesis for adaptation strategies including participatory research.

The scope of this report focuses on moving beyond purely economic or biophysical risk assessments, which were summarized in the previous Deliverable 2.2. We now concentrate on quantifying and characterizing the often less-monetized aspects of vulnerability, particularly societal and human dimensions, to provide a holistic view of Socio-Economic (SE) risks.

1.2. Objectives of Task 2.3

Task 2.3, titled *Impact model simulations and assessment of context specific SE risks, including mitigation and adaptation options for STL case-studies*, has the central objective of generating integrated, actionable insights at the local scale.

This report addresses the following key objectives for each case study, complementing the earlier findings presented in Deliverable D2.2:

- Analyze Socio-Demographic Disparities: To quantitatively and qualitatively assess how gender and other dimensions of social inclusion (e.g., age, income, social isolation) shape differential exposure, sensitivity, and adaptive capacity across population sub-groups.
- Assess Human Capabilities: To evaluate how climate hazards impact fundamental human capabilities (e.g., *Bodily Health, Bodily Integrity, Play*)

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for affected communities, employing frameworks such as Amartya Sen's Capability Approach to reveal the true burden of risk.

- Integrate Ecosystem Aspects: To analyze the influence of ecosystem conditions and services, such as Blue-Green Infrastructure (BGI), on both vulnerability and the effectiveness of Mitigation and Adaptation (M&A) strategies.
- Synthesize and Prioritize Action: To translate the combined quantitative and qualitative evidence into a clear synthesis of key findings and actionable priorities, for action aimed at enhancing local and regional resilience

1.3. Structure of the Report

The remainder of this report is organized as follows:

- Section 2: Case Study Assessments: This section presents the integrated quantitative and qualitative findings for seven of the eight CROSSEU case studies (CSAs 1 to 8). For each CSA, the key risks are summarized, unresolved technical/ecosystem issues are addressed, and a focused Assessment of Societal and Human Vulnerabilities is presented, concluding with a synthesis of priorities for action.
- Section 3: Cross-Cutting Synthesis: This section provides a horizontal, comparative analysis across all completed CSAs to identify common themes in European climate vulnerability, including a consolidated synthesis of the gender and social inclusion dimensions, and a framework for upscaling and overarching policy priorities.
- Section 4: Conclusion and Recommendations: This final section summarizes the main achievements of D2.3 and presents the overall recommendations to inform the wider CROSSEU Decision Support System (DSS) and future policy guidance (WP3 and WP4).

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2. Case Study Assessments

2.1. #1 HEAT

2.1.1. Summary of Key Risks from D2.2

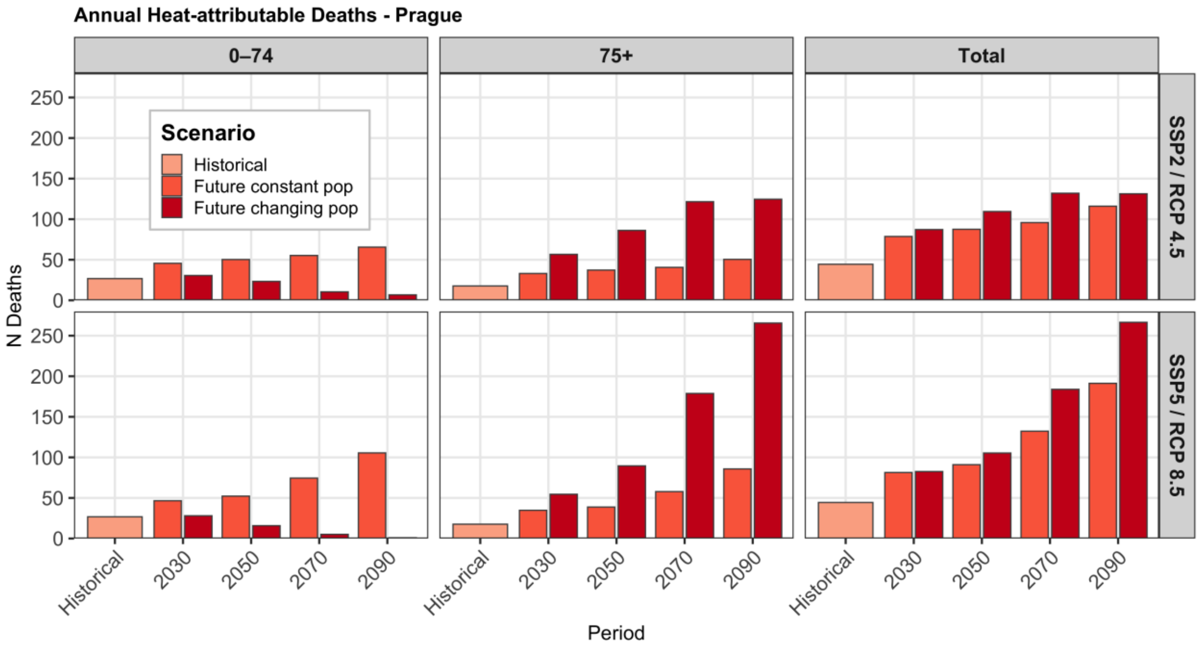
Results of CSA1 in D2.2 suggested that the recently observed trend in increasing heat-related mortality burden in the Czech Republic will continue if no adaptation takes place. Specifically, in Prague our CROSSEU findings indicated that by the end of the century (2090s, RCP 8.5), we can expect more than 230 heat-attributable deaths annually, compared to 50 annual heat-related deaths in the 2000s. Accounting for age-stratified temperature-mortality association (0-74 and 75+ years old) and including EUROSTAT population scenarios (EUROPOP2019) in the future projections revealed that, in some regions, the burden of heat-related mortality will be substantially aggravated by demographic changes. Therefore, the nationwide heat impact is projected to increase from the current 290 to as many as 1500 annual heat-related deaths by the 2090s (RCP 8.5).

Our CROSSEU findings highlight the important role of demographic patterns when estimating the future mortality burden associated with extreme temperature events within regions. Such demographic patterns are driven not only by the balance between national natality and mortality, but also by intra- and inter-national migration flows. In the follow-up analysis presented in the following sub-sections, we account for these dynamics by incorporating alternative population scenarios based on migration storylines informed by the Shared Socioeconomic Pathways (SSPs) obtained by the Wittgenstein Centre Human Capital Data Explorer (European Commission 2018).

2.1.2. Supplementary issues related to D2.2

Using the same epidemiological approach as in D2.2 (pp. 27–28), we employed two new combinations of SSP/RCP scenarios to compare alternative futures in terms of climate and demographic changes. While the SSP2/RCP4.5 scenario represents a "middle road" socio-economic pathway with moderate GHG emissions, medium fertility and mortality rates, the SSP5/RCP8.5 scenario combines a high-emission scenario with low fertility, low mortality and high-migration assumptions.

CSA1_Figure1 shows that heat-attributable deaths in Prague increase across future periods in both age groups and both scenarios from historical. The SSP5/RCP8.5 scenario was associated with an increase in heat-attributable deaths up to 267 annual deaths by the 2090s in Total population, compared to 234 deaths in the previously run EUROPOP2019 scenario. Nation-wide, the high-emission scenario was associated with approx. 2000 annual heat-attributable deaths in the 2090s, compared to approx. 1500 deaths estimated in D2.2. These results underscore the important role of population ageing in estimates of the future CC impacts on temperature-related mortality.



CSA1_Figure1: Historical and future distribution of annual heat-attributable deaths in Prague, Czech Republic, under SSP2/RCP 4.5 and SSP5/RCP 8.5 scenarios, with (future constant pop) and without (future changing pop) population aging, stratified by age groups.

The role of age, gender, and SE status

Employing state-of-the-art multivariate meta-regression analysis (Sera et al. 2022), our analysis did not reveal significant effects of socioeconomic factors (e.g. GDP, level of unemployment, proportion of elderly) on the spatial distribution of the heat-related mortality risk at the NUTS 3 level. This is in line with previous findings that identified the level of exposure to the excessive heat (i.e. population density combined with magnitude of the physical hazard) as the main driver of the heat impact differences across the country (Urban et al. 2016).

However, population subgroups divided by individual characteristics such as age and marital status showed significant differences in the level of heat-related mortality risk (Vésier & Urban 2023; Jánoš et al. 2024). Additionally, while elderly and chronically ill women face the largest risk of heat-related mortality (*ibid.*), children and youth are at the highest risk of heat-related hospitalizations and ambulance dispatches (Jánoš et al. 2025, Mühlhaus et al. 2025).

While many studies suggest higher heat-associated risk of mortality in women (Son et al. 2019) this was not seen in England in the analysis of 2024 (Heat mortality monitoring report, England: 2024 - GOV.UK). These findings highlight that local specific dynamics in the proportion of vulnerable population groups need to be considered in the development of regional adaptation strategies.

2.1.3. Ecosystem aspects in results

Increased use of blue-green infrastructure (BGI) has been considered the most efficient ecosystem solution to mitigate the level of exposure of urban populations to excessive heat (see also part 2.1.5). Numerous studies have investigated the ability of selected solutions to mitigate urban heat. The cooling potential of BGI is largely dependent on the scale of interest, i.e. the shape and size of the selected feature (Wong et al. 2021). For example, Kumar et al. (2024) reviewed more than 200 studies to find that large city features combining the effect of water and vegetation such as big parks, botanical gardens, and wetlands have the largest cooling efficiency. Similarly at the microscale level, solutions based on the water effect or the combined effect of water and greenery have been documented as the most efficient in cooling urban pavements and their immediate surroundings (Wang et al. 2021).

Although there has been some evidence of the beneficial effect of BGI in reducing heat-related health risks (Choi et al. 2022, Wu et al. 2025), these findings are rather hypothetical (based on the physical hazard modelling) due to limited spatial resolution of health data and limited information about the actual location of individual cases. In addition, spatial distribution of the most vulnerable population groups in the city may significantly modify the heat-vulnerability map at the local (city) level (Wolf et al. 2013).

Implementation of BGI in Prague and London

Prague and London, two case-study cities in the HEAT storyline, have implemented climate change adaptation and mitigation strategies (see more in D4.1–4.2) that include specific targets regarding the implementation of BGI.

Prague

Climate Plan of the City of Prague (City of Prague 2021, pages 104–127) introduces 10 specific measures with the aim to improve the quality of life in the city via improvement of microclimatic conditions, increased share of greenery, decreased share of impervious surface, implementation of a sustainable drainage system, enhanced adaptation of buildings and public spaces, and improvements of the heat risk management. Implementation of these solutions for the years 2025–2029 has been detailed in the Implementation Plan of the Climate Change Adaptation Strategy of the City of Prague (City of Prague 2024).

London

The London Climate Resilience Review report has evaluated risks and recommended actions to prepare for extreme weather including the need for a London-wide action plan on heat risk (Howard Boyd et al, 2024). Since

2016, £30 million has been invested in green projects across London, including planting trees, accessible green spaces and investment in green roofs and walls. Further recommendations include a commitment to increase tree canopy cover by 10% by 2050, targeting areas and communities that currently have limited BGI. Recommendations suggest support via grants for local and regional organisations and calls to prioritise BGI in built environment work.

However, limitations have also been noted, such as maintenance costs associated with BGI. During the 2022 heatwave there was widespread failure of green infrastructure including loss of trees from fire and newly planted trees from water scarcity *(ibid.)*. The report also emphasises that BGI should not increase fire risk. Anecdotal evidence suggests the trade-off between benefits of BGI versus additional fire risk may be influencing a shift away from BGI in certain cases.

2.1.4. Gender and social inclusion Dimensions – The efficiency of heat adaptation strategies in Europe

Heat prevention plans (HPPs), including policies such as heat-health warning systems and heat-health action plans, are universally considered key public health interventions to reduce health impacts of heat (Toloo et al 2013, McGregor et al 2015, Casanueva et al 2019). While adopted in many countries, evidence on the effectiveness of HPPs in reducing heat-related health risks is still limited (Dwyer et al 2022). In collaboration with the Multi-Country Multi-City (MCC) Collaborative Research Network and the COST Action PROCLIAS, our CROSSEU case study analysed the efficiency of HPPs in reducing heat-related mortality risk in selected European countries and cities (Urban et al. 2025).

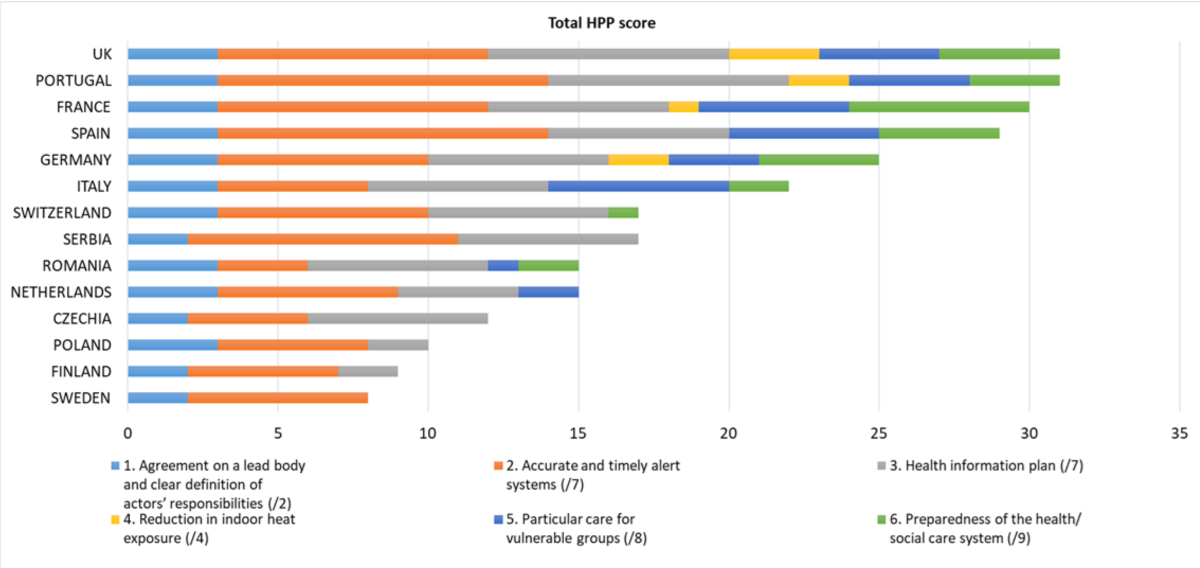
Data and Methods

We analysed daily mortality and mean temperature data from 102 locations in 14 European countries, including Prague and London, between 1990 and 2019. Using data from national experts, we identified the year of HPP implementation and classified their development level based on the number of the WHO core elements (see McGregor et al 2015) implemented in the national HPPs (via a HPP score, see CSA1_Figure 3). A three-stage analysis was conducted: (1) quasi-Poisson distributed lag non-linear models (Gasparrini 2014) were used to estimate location-specific warm-season exposure-response functions in three-year subperiods; (2) mixed-effect meta-regression models with multilevel longitudinal structures (Sera et al 2022) were employed to quantify changes in pooled exposure-response functions due to HPP implementation, adjusted for long-term trends in heat vulnerability; and (3) the reduction in heat-related excess mortality related to HPP implementation was calculated by comparing factual (with HPP) and counterfactual (without HPP) scenarios.

Results

HPP development

Data from 14 countries that provided suitable mortality as well as HPP data were included in the final analysis. The HPP scores are shown in CSA1_Figure 2, with the UK and Portugal scoring the highest, having implemented actions across all core elements. Scandinavia (Sweden and Finland) and central-Eastern Europe (Czechia and Poland), on the other hand, scored the lowest due to having heat alert systems with no follow-up actions.



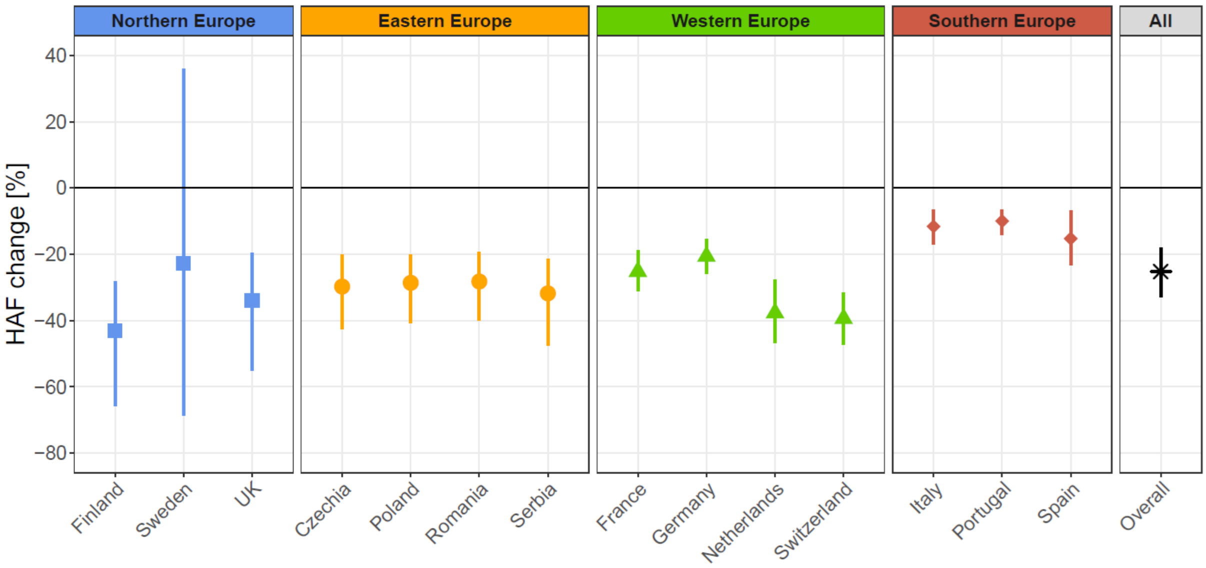
CSA1_Figure2: HPP score in the countries based on the WHO core elements analysed in the study. Maximum potential score for each element is stated in parentheses.

In Czechia specifically, a nation-wide severe weather (including heat) warning system with HPP score = 12 (max possible HPP score was 35) was implemented by the Czech Hydrometeorological Institute in 2000. The heat warning system issues alerts for high temperatures on a three-level scale (high temperature = Tmax > 31°C, very high temperature = Tmax > 34°C, extremely high temperature = Tmax > 37°C) for 76 districts in Czechia (Prague being one of those 76 districts). Despite several updates in the heat warning system and dissemination of heat alerts (together with recommendations for heat-vulnerable groups) to the public, media, as well as national and regional stakeholders, the heat alerts are not linked with any heat action plan.

In England, on the other hand, the Heat Health Watch Service, implemented by Met Office and Public Health England in 2004, has been connected with the Heat Wave Plan (https://assets.publishing.service.gov.uk/media/5a7c83bde5274a559005a655/dh_127235.pdf), defining a comprehensive set of action initiated after a heat alert issuance. England's HPP (defined as the UK in CSA1_Figure 2) ranked as the most complex from all locations in our study (HPP score = 31).

The health effects of HPP implementation

HPP implementation was associated with 25.2% [95% CI: 19.8% to 31.9%] reduction in excess deaths attributable to extreme heat across all study locations. This reduction corresponded to 14,551 [95% CI: 10,118 to 19,072] total deaths avoided following HPP implementation (CSA1_Figure3). In Prague and London, specifically, HPP implementation was associated with the reduction of heat-attributable deaths by 26.2% [95% CI: 18.0 to 36.4%] and 24.6% [95% CI: 9.5 to 44.1%], respectively. This reduction was equivalent to the total of 505 [95% CI: 356 to 668] and 1062 [95% CI: 453 to 1757] heat-related deaths avoided since HPP implementation in Prague and London, respectively.



CSA1_Figure3: Change in heat-attributable mortality fraction (HAF change – quantified as a relative difference between the counterfactual and the factual scenarios) per country associated with HPP implementation. Error bars indicate 95% empirical confidence intervals calculated by Monte-Carlo simulations.

Although our findings provide robust evidence that HPPs substantially reduce heat-related mortality across Europe, the hypothesis that more developed HPPs result in a stronger protective effect was not proved. This may reflect large uncertainties associated with the HPP data collection and evaluation. In each country, the effective operation of individual HPP elements is subject to actual implementation at the regional and local scale, which is influenced by various factors, such as the amount of financial and human resources provided for HPP implementation, the level of harmonization between national and regional action plans, or the level of involvement of local health and social institutions (Martinez et al 2022). In addition, despite the rather complex study design that aimed to adjust the effect of HPPs for long-term trends in heat-vulnerability (details available in Urban et al. 2025), the analysis could not capture the role of all possible confounding factors, such as continuous development and updates of HPPs in individual countries.

For example, England's Heatwave Plan was replaced in 2023 by the Adverse Weather and Health Plan which included a shift from temperature-based thresholds to impact-based thresholds for the early warning system. A recent analysis of this change highlights it was well received by practitioners but that there is still a barrier in overcoming the publics 'positive' perception of warm weather, limited consideration of wider impacts beyond the health sector, and a short-term focus that ignores the need for longer term planning and resilience to heat (Ravishankar & Howarth 2024).

This example highlights the need for intensified cross-border exchange of the good practice in development and implementation of HPPs, including a standardised evaluation of national and regional HPPs and a larger focus on long-term adaptation measures (Martinez et al 2022). Literature also highlights lack of actions focusing on specific vulnerable groups, such elderly and chronically ill, outdoor workers, or pregnant women and infants (Martinez et al. 2022).

2.1.5. Assessment of Societal and Human Vulnerabilities

Qualitative Findings from Stakeholder Engagement

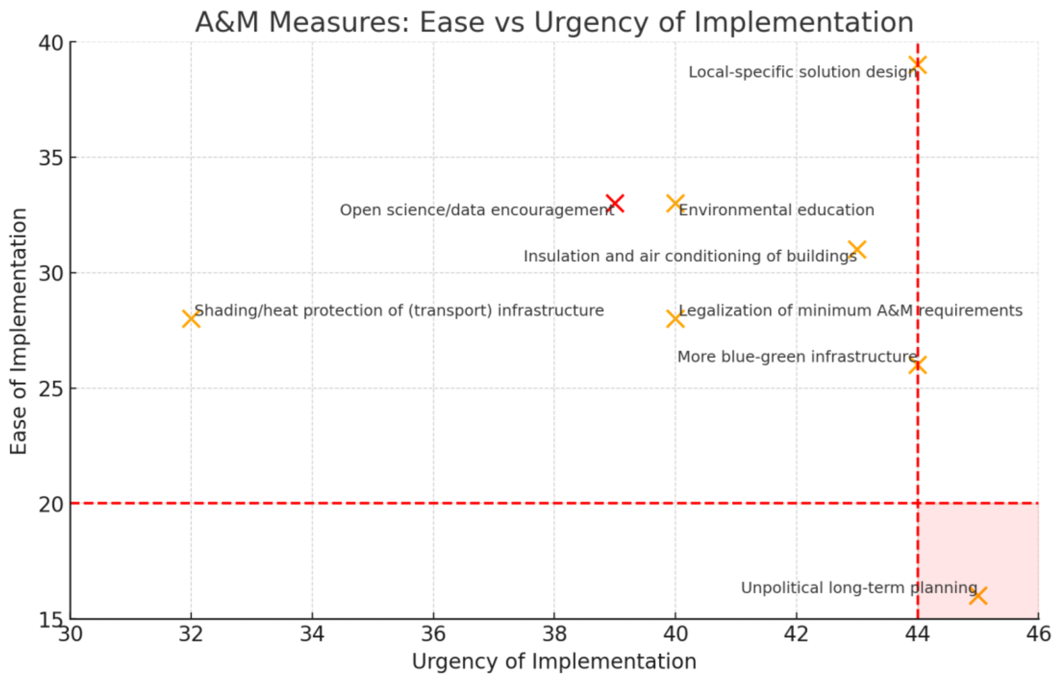
The efficiency of heat-mitigation and adaptation measures, in terms of reducing the actual heat-related mortality risk, is substantially driven by long-term changes in socio-economic vulnerabilities (Boeckman et al. 2014). To better understand the local specific societal vulnerabilities, the CSA 1 team organized a stakeholders' workshop on the "Resilience to urban heat", hosted by the City of Prague in partnership with local representatives of the CROSSEU and CARMINE (https://carmine-project.eu/) projects (https://praha.eu/web/portalzp/w/konzult-setkani-s-workshopem-odolnost-mestskeho-prostredi-vuci-horku-112024). The event brought together 31 stakeholders from academia, public health, city planning, and civil society to co-explore socioeconomic barriers, challenges and solutions for efficient heat risk management. During the workshop, 10–15 participants (varies between individual questions) responded the survey on Socioeconomic Risks and Barriers in the Climate Risk Management and engaged in the follow-up discussion on the main CC challenges in Prague/Czech Republic and related socioeconomic risks (https://crosseu.eu/news-How-will-heatwaves-shape-Pragues-future).

Key findings of the workshop included:

- Heatwaves were identified as the top climate hazard for Prague.
- Elderly, socially isolated, and low-income groups were identified as those most vulnerable to extreme heat.
- Political short-termism, low public awareness, and limited understanding to climate data were named as the main socio-economic barriers for the most efficient heat risk management.

Unpolitical long-term planning, environmental education, and increased BGI were identified as the most important solutions to mitigate heat risks in Prague (CSA1_Figure4).

The stakeholders also identified changing demographic structure and distribution as the main factors affecting the vulnerability of population to heatwaves. These findings supported our activities in CSA 1 that focus on the role of population ageing when assessing the impact of climate change on heat-related mortality.



CSA1_Figure4: Prioritization of adaptation and mitigation (A&M) solutions to excessive heat risk management in CSA 1 (Prague, Czech Republic). The plot axes represent the final urgency (x-axis) and ease (y-axis) score as a cumulative vote of 10 participants, who ranked the individual solutions on a scale from 1 (hardest, least urgent) to 5 (easiest, most urgent).

Capabilities Impacted

Based on the outputs from the stakeholder workshop, we developed a list of capabilities impacted by extreme heat based on Amartya Sen's Capability Approach (Sen 1999). Together with the outcomes of the stakeholder workshop, this list helps to identify the practical needs of different population groups during hot weather. Although the exercise was performed for the Prague Case Study, the main findings are applicable also for London (see Section 3).

We identified 11 key capabilities potentially affected by hot weather (CSA1_AnnexTable1), most of which relate to people's living conditions, such as access to shaded public spaces, cooling facilities (public buildings, shopping malls, etc.), safe places for recreation, and reliable public information. 3 of the identified capabilities focus on basic needs, such as sufficient access to fresh drinking water and food during heatwaves. Being

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able to maintain good health was identified as the main "basic need" capability, as it is directly related to the level of heat vulnerability.

The assessment highlights several groups that are especially vulnerable. Previous results showed that while elderly and chronically ill people are most vulnerable to heat-related mortality risks, children and youth emerge as the most-at-risk group when considering heat-related morbidity (ambulance calls and hospitalizations – Section 2.1.2).

Across the capabilities, common challenges include high exposure to heat, unequal access to cool or shaded areas, limited awareness of heat risks, and pressure on the city's public spaces and infrastructure. At the same time, the analysis shows strong opportunities for action, such as expanding green and shaded areas, improving access to cooling centers and drinking water, adapting youth programs for hot weather, strengthening home insulation, and providing clear, inclusive public communication – especially for young people, tourists and language minorities.

2.1.6. Synthesis and Priorities for Action

Updated results of CSA 1 confirmed that heat-related mortality in the Czech Republic is projected to increase substantially, driven by both climate change and especially population ageing, with nationwide deaths potentially rising five- to seven-fold by the end of the century if no adaptation takes place. While regional socioeconomic characteristics explained little of the spatial variation in heat-related mortality, individual characteristics – particularly age, social isolation (divorced and widowed elderly), and chronic illness – remain important determinants of heat-vulnerability. A European wide analysis revealed that HPPs reduce mortality by around 25%, although effectiveness varies widely depending on implementation rather than plan complexity.

Stakeholder engagement highlighted low public awareness, fragmented institutional coordination, and political short-termism as the major barriers to effective heat risk management. To reduce rising impacts of heat waves on public health, cities and governments need to consider the local demographics in their climate-health planning. This includes strengthening HPPs and focusing their actions on the most vulnerable population groups, which are not only elderly and chronically ill people, but also children and youth. Such actions should include expanding access to cooling, shade, drinking water, and safe indoor/outdoor spaces for vulnerable population groups. This should be complemented by strategic investment in BGI that needs to be designed, maintained, and governed to remain resilient under heat stress.

2.2. #2 DROUGHT

2.2.1. Summary of Key Risks from D2.2

CSA2 Drought analysed drought characteristics and impacts in the present and in the future climate over five selected hotspots located in Central and South-East Europe. Results enhance the understanding of the drivers generating bio-physical, economic and societal risks associated with different climate scenarios. The analysis highlighted a significant increase in drought hazard intensity, especially towards the late 21st century in southern and western Europe. Regions in Greece, Italy and in Romania are expected to face more frequent, more intense, and longer lasting drought events. Selected hotspots differ in relation to social vulnerability. For example, Romania and Poland currently present a higher dependency on agriculture, while Germany is characterised by a higher adaptive capacity. Consequently, drought risk is unevenly distributed. Some hotspots—particularly in southeastern Europe—face extreme risks due to the convergence of high hazard levels and socio-economic sensitivity.

2.2.2. Supplementary issues related to D2.2

Impact data like population density, agricultural labour force, or irrigable land share characterize present socio-economic conditions and, thus, offer valuable insights into current exposure and adaptive capacity. However, these indicators do not capture dynamic trends or future socio-economic developments that could alter risk profiles. Moreover, the granularity of some of the available socio-economic data (e.g., NUTS2 level for density, agricultural labour force, irrigable land share) often limits the precision of the analysis, especially in rural and transboundary regions where agricultural practices and vulnerabilities vary significantly over short distance.

The available number of socio-economic indicators used to assess impact and vulnerability as well as their static nature limit the completeness of any assessment of drought risk over the targeted areas.

2.2.3. Ecosystem aspects in results

Drought impacts on ecosystem services cover a variety of services. These include (i) regulating services like water availability, water quality, and soil erosion, (ii) provisioning services regarding, e.g., crop yields, forest products, (iii) cultural services like recreation through the impact on landscape and rural tourism, and (iv) supporting services, like water retention or soil retention.
The analysis presented here regards the drought impact on regulating services and in particular on land degradation. This pertains to ecosystem services relevant for all selected hotspots in the form of agricultural land, forested areas, or protected areas.

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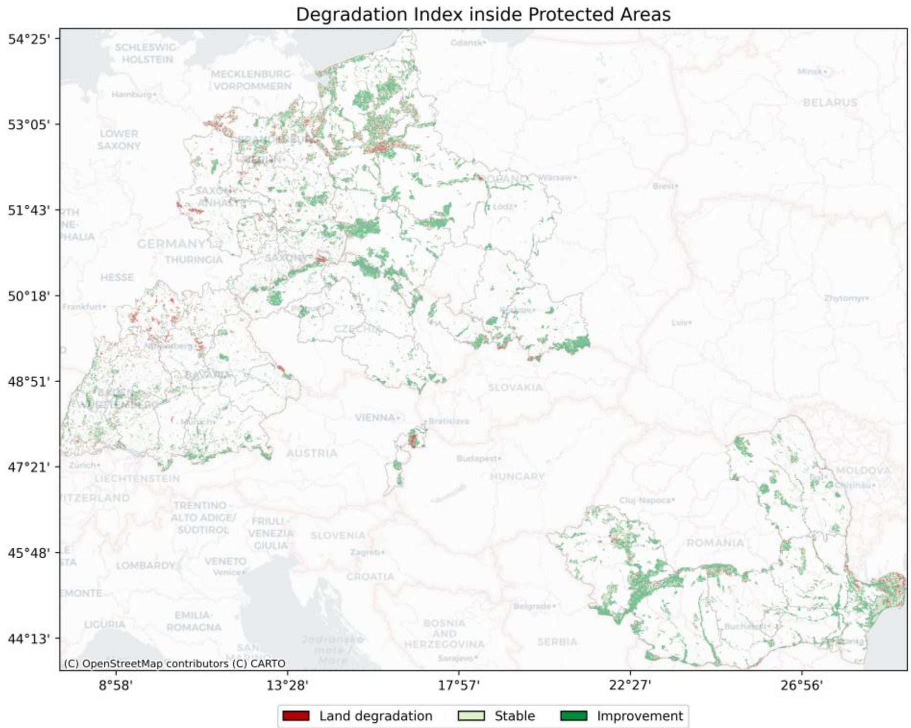
Methodology: Degraded land was identified based on the analysis of spatio-temporal trends of key biophysical indicators derived from Terra MODIS satellite imagery for the period 2000–2025, following the methodology proposed by Ontel et al. (2023). The assessment of long-term trends in these indicators allows for the detection of persistent ecosystem changes, revealing processes of land degradation or improvement in vegetation productivity, soil moisture, and surface energy balance (Yue et al., 2002; Forkel et al., 2013). The analyses used the following MODIS-derived variables at a 1 km spatial resolution: Normalized Difference Vegetation Index (NDVI), Net Primary Production (NPP), Total Evapotranspiration (ET), Land Surface Temperature (LST), Black Sky Albedo (BSA).
Trend analysis was employed to detect the direction (positive or negative) and statistical significance of changes over time in each biophysical variable. To integrate and interpret complex relationships among multiple biophysical indicators, a Principal Component Analysis (PCA) was applied. The identified underlying patterns and correlations among NDVI, NPP, ET, LST, and BSA, facilitate a holistic interpretation of degradation processes within the terrestrial system.

The extracted principal components were subsequently used in an Ordinary Least Squares (OLS) regression model to quantify the contribution and statistical significance of each component to land degradation dynamics. The combined use of PCA and OLS ensures a robust, non-redundant analytical framework that mitigates multicollinearity and allows for a clearer interpretation of the spatial interactions among biophysical parameters.

Results: The spatial assessment of the Degradation Index within protected areas, aggregated at the NUTS2 level, shows that most protected territories remain either ecologically stable or exhibit signs of improvement (CSA2_Figure1). Degradation signals occur only in small, scattered patches, and do not form regionally consistent hotspots. An exception is visible in southern Germany, where four NUTS2 regions in Bavaria display more noticeable and spatially clustered degradation within protected areas. Additional areas with elevated but more fragmented degradation can also be observed in eastern Germany, particularly in Saxony, and in western and southern Poland, although these patterns are less regionally consistent and do not form clear hotspots at the NUTS2 scale. Outside these localized concentrations, both Germany and Romania display localized instances of degradation, which are isolated and do not dominate the ecological profile of their protected areas. Overall, protected sites across Central and Eastern Europe appear to fulfill their conservation role effectively, maintaining ecosystem integrity and demonstrating high resilience to land degradation pressures.
Across the NUTS2 regions considered, the share of protected areas affected by land degradation is relatively low. Stable or improving conditions are

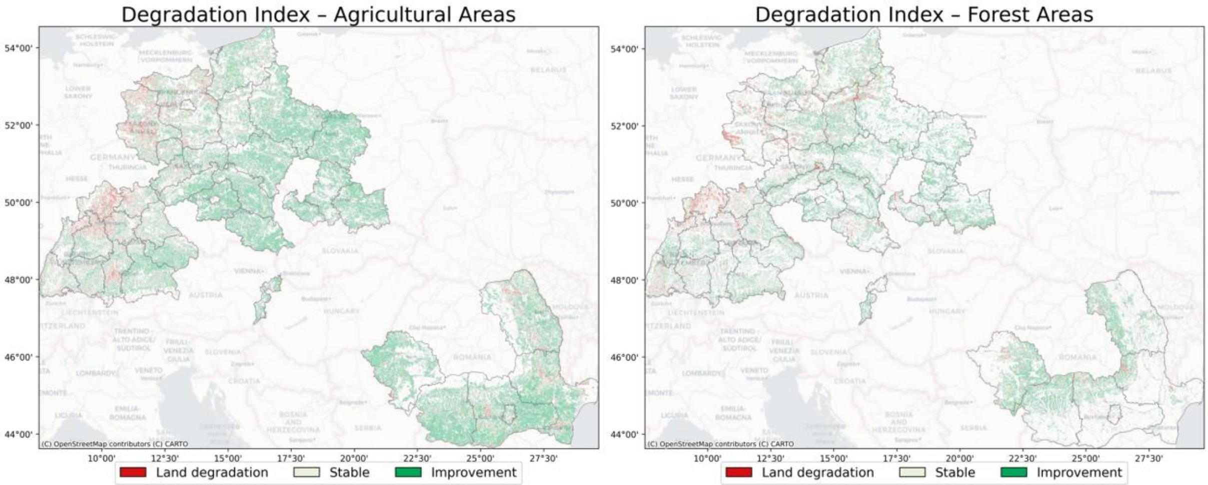
more prominent in most regions. The stacked bar chart in CSA2_Figure2 highlights a consistent pattern: in the majority of NUTS2 units, more than 70 to 90 percent of the protected surfaces fall within the “improvement” or “stable” classes. Degradation is present but generally limited, often below 10 percent of the protected area, with only a few regions displaying higher values. Notable exceptions occur in several German Bavarian and Saxony regions (such as DE23, DE24, DE25, DE26, and DED5), which form a geographically coherent cluster where degradation reaches between 20 and 45 percent. This localized hotspot contrasts with the broader regional pattern. In contrast, the Czech, Austrian, Polish, and Romanian regions show predominantly low degradation rates, typically under 15 percent.



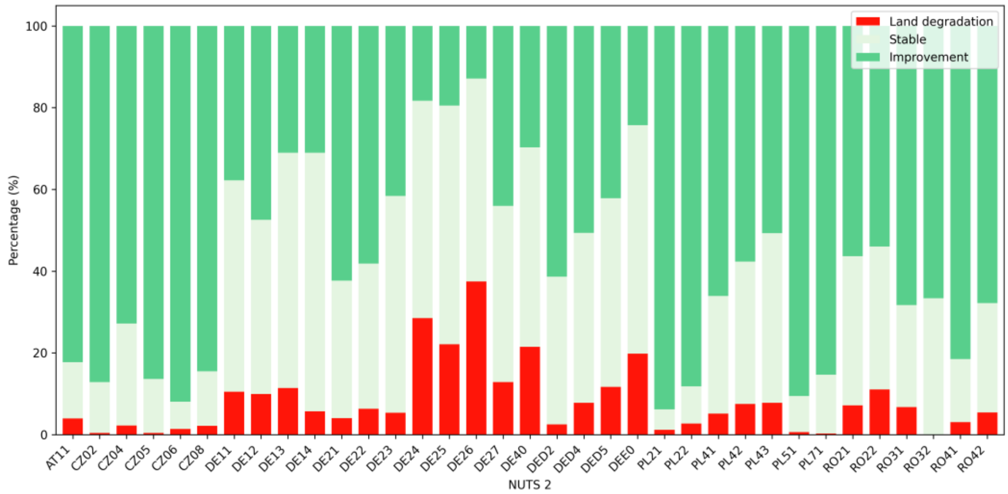
CSA2_Figure1. Spatial distribution of land degradation inside protected areas.

CSA2_Figure2: Land degradation percentage inside protected areas per NUTS 2.

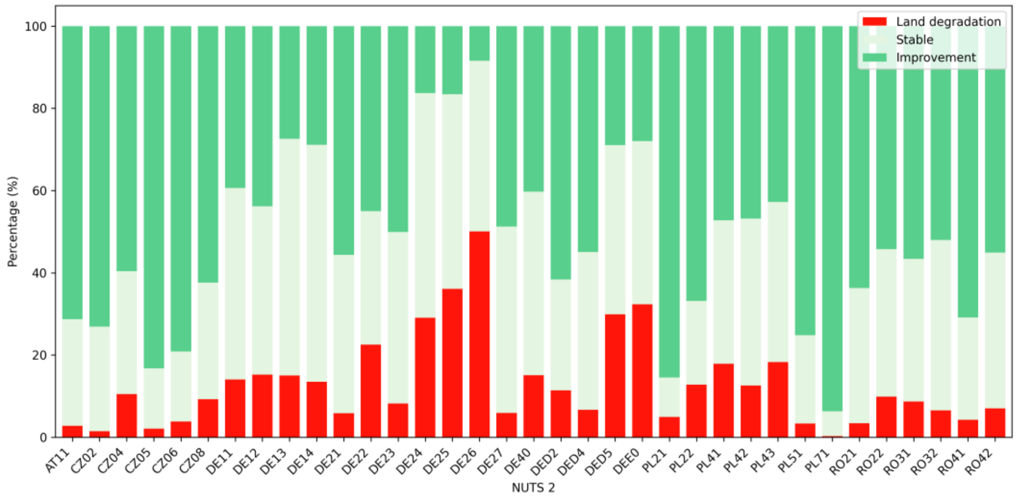
CSA2_Figure3 illustrates the spatial distribution and relative proportions of land degradation, stability, and improvement across NUTS 2 regions within the study area, separately for agricultural (left) and forest (right) lands. Most regions exhibit a predominance of stable or improving conditions (represented in light and dark green). Land degradation (in red) remains generally limited and spatially dispersed; however, several regions exhibit noticeably higher shares. These occur primarily in Germany, most prominently in a number of Bavarian NUTS2 units and in Saxony, where degradation reaches substantially higher levels in both agricultural and forest areas. A smaller number of Polish regions also show elevated degradation values, though with less spatial coherence. The bar charts below each map (CSA2_Figure4 and 5) quantify these patterns, showing the percentage share of degraded, stable, and improved land in each region. In both agricultural and forest areas, the majority of regions display a high proportion of improvement and stability, suggesting positive or neutral land condition trends. However, certain regions in Germany (Bavarian and Saxony NUTS2 units) and a smaller number of Polish regions show higher shares of degradation, indicating localized pressures on land productivity or ecosystem health.



CSA2_Figure3. Spatial distribution of land degradation inside agricultural and forest areas



CSA2_Figure4. The percentage of land degradation inside agricultural areas



CSA2_Figure5. The percentage of land degradation inside forest areas

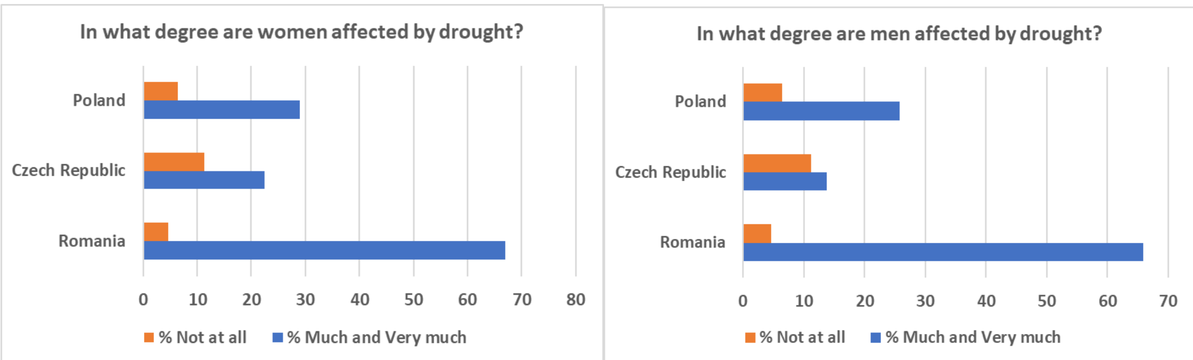
2.2.4. Gender and social inclusion dimensions

We approach the gender and social inclusion dimensions of drought using an online survey that gathers insights on the individual perception of drought impact. The survey was distributed through the LinkedIn channel of the CROSSEU project as well as through personal and professional networks of researchers involved in CSA2, either in the national language or in English, aiming to cover all countries where drought-related hotspots are located, i.e., Romania, Czech Republic, Poland, Germany and Austria. The target audience of the survey covers people residing and/or working in urban and/or rural areas, of age above 18 years. The survey includes three main parts: (i) social and demographic data, collecting anonymous information on the country of residence, living and working environment (urban/rural), age, and education level; (ii) perceived type of impact/capabilities impacted – related to health, income/economic impact, food security, public services, leisure, security; (iii) perceived gender-differentiated impact, considering 10 social categories (women, men, children, seniors, people with chronic medical conditions, people without stable income, people living in plain/hilly areas, people living in urban/rural areas).

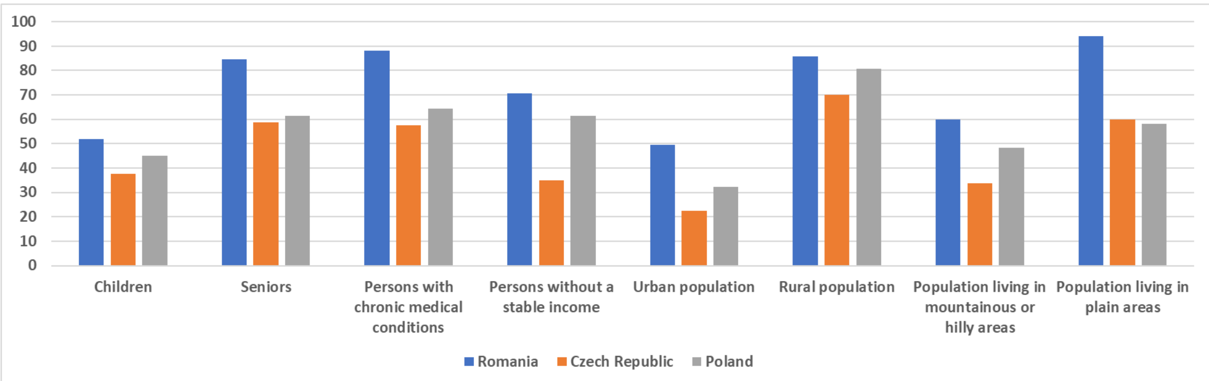
The present analysis is based on the responses received during the period 31 October –10 November; the sample sizes consist of 85 responses for Romania, 80 responses for Czech Republic and 31 responses for Poland, . The number of responses is directly related to the dissemination channels and time allocated for receiving answers (10 days). The results for Czech Republic and Romania have a confidence level of 90% with a margin of error of 10%; for Poland, the confidence level is 75% with a margin of error of 10%; for all cases, the population size is considered the country population aged 20-84 years, based on EUROSTAT data from 2021 census.

Socio-demographic analysis and perceived drought hazard: The socio-demographic characteristics of the respondents are similar for all three countries. They are mainly living and working in big urban areas (51-61%), with high educational level (university and post-university), in the age interval 25-65 years (86-93%) and almost equally divided between men and women; respondents working in rural areas are mainly found in Romania (48%) followed by Poland (25%), while only 8% of the respondents from Czech Republic are working in rural areas. For all three countries, most of the respondents (55-80%) acknowledged that drought manifested in their living or working area ‘often (e.g., at least 5 years in the last 10 years)’.

Results: The preliminary analysis highlights differences in the perceived impact between the countries of residence (CSA2-Figures 6 and 7. A larger share of Romanian respondents perceives high intensity impact on both women and men as well as on all eight social groups considered, compared with respondents from Czech Republic and Poland. On the other hand, respondents from Czech Republic seem to perceive the least a high impact of drought on either social group considered. Most respondents in all three countries appreciate that rural population is affected 'much' and 'very much' by drought, on second place being people with chronic medical conditions; also, urban population is generally perceived as not being strongly affected by drought. Another preliminary conclusion regards perceived impact by women respondents from Czech Republic and Poland, who perceive a higher impact on women than on men, while men respondents practically do not 'observe' a gender-related difference in the high-level impact (i.e., 'much' and 'very much' categories). On the contrary, in Romania about 66% of both men and women respondents consider that men and women are affected 'much' and 'very much' by drought. The more pronounced perceived impact on women, by women, in Czech Republic and Poland, seems to be in line with other research (e.g., (McDowel et al, 2020; Brown et al, 2021) suggesting that women are more sensitive to (climate-related) risks.



CSA2_Figure6. Share of survey respondents considering that (a) women and (b) men are affected 'very much' and 'much' or 'not at all' by drought, based on the responses for Romania, Czech Republic and Poland.



CSA2_Figure7. Share of survey respondents considering that social groups generically represented by 'children', 'seniors', persons with chronic medical conditions', persons without a stable income', 'urban population', 'rural population', 'population living in mountainous or hilly areas' and 'population living in plain areas' are affected 'very much' and 'much' by drought, based on the responses from people living in Romania, Czech Republic and Poland.

The analysis is limited by several factors, among which the quite low sample sizes for each country and particularly for Poland, under-representation of population living and/or working in rural areas and the lack of information on income level may be considered as most important.

2.2.5. Assessment of Societal and Human Vulnerabilities

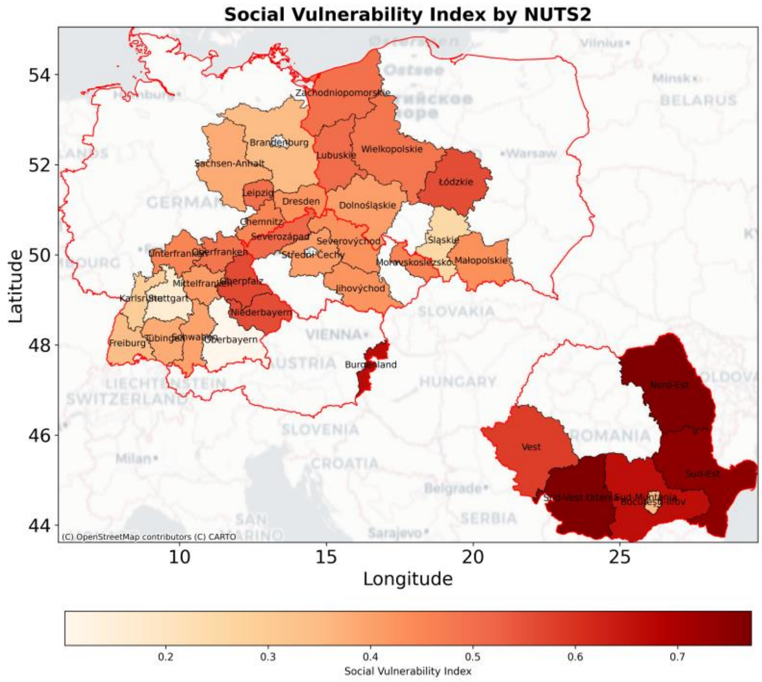
The analysis of social vulnerability in CS#2-Drought follows the current literature (e.g., Naumann et al, 2019; Serkendiz and Tatli, 2023; Meza et al, 2019; Vieira et al, 2024) and adapts these approaches to the specifics of the case study. The focus is on the social and economic dimensions of vulnerability (JRC, 2023) and the quantitative indicators should cover all selected hotspots, located in five different countries, for the same time period, which limits to some degree their selection.

Data and methods: The analysis includes the social and economic dimensions of vulnerability (JRC, 2023). These are described by four quantitative indicators provided by EUROSTAT at NUTS2 level and relevant in relation to drought hazard, namely persons at risk of poverty or social exclusion (2019), population (age 15-64) in private households by educational attainment level, main agricultural labour force (2023), and income of households (2022) and (CSA2Annex-Figure1).

For each indicator, the values are normalized taking into account the maximum and minimum values among all selected NUTS2 regions; the approach accounts for the positive/negative correlation with vulnerability level (Naumann et al, 2019).

The social vulnerability index (SVI) was computed as the arithmetic mean of the four indicators, for each of the selected NUTS2 regions. There are three regions (AT11-Burgenland, DE22-Niederbayern, DE23-Oberpfalz) for which no data was available to assess the 'social inclusion'; for these regions, SVI was computed from only three indicators.

Results: The analysis indicates that NUTS2 regions in Romania have, in general, the highest social vulnerability to drought, while German regions present the lowest social vulnerability. (CSA2-Figure8). North East, South East and South-West Oltenia regions in Romania and Burgenland region in Austria present the highest values of SVI index; these regions are characterized in principal by a low income (e.g., Burgenland, South-West Oltenia), a high dependency on agriculture (e.g., North East) and a high share of population at risk of poverty or social exclusion (e.g., North East). At the opposite side, Oberbayern and Stuttgart (Germany) regions present the lowest SVI values in relation to drought (i.e., below 0.2), followed by Karlsruhe (Germany) and Śląskie (Poland). A common feature for these regions is the low labour force in agriculture, which makes them less vulnerable to drought.



CSA2-Figure8 Social Vulnerability Index at NUTS2 level, for areas included in the selected hotspots.

The results suggest that improving social inclusion (i.e., a lower share of population at risk of poverty or social exclusion and increasing/diversifying the income sources (i.e., higher income, lower dependency on agriculture) would reduce the vulnerability to drought. While the dependency on agriculture is more difficult to reduce, adaptation options in the agriculture sector can ensure more stable productions and income. These, thus, can contribute to a reduction of social vulnerability to drought in some regions.

Qualitative Findings from Stakeholder Engagement

As part of the strategy regarding stakeholders' involvement in the project, a survey was disseminated in December 2024-January 2025 targeting potential stakeholders from several socio-economic sectors, aiming to get insights on their perspective on the socio-economic impact of drought. The survey, distributed online, had a response rate of 70% and collected views from 67 stakeholders activating in 11 socio-economic sectors (research and development, agriculture, biodiversity, public administration, education, tourism, forests, water resources, energy, environmental protection, health). Around 66% of the respondents activate in urban areas; the institutions they represent are mainly public institutions (53 respondents) followed by private institutions (12 respondents) and NGO (2 respondents).

The survey results highlight the perception of drought as a natural disaster with spill-over effects in practically all socio-economic sectors considered. Furthermore, respondents identify agriculture and water as the most affected sectors. Results identify a negative influence of drought on the food supply, leading to an increase in prices especially for cereals, fruit, and vegetables. Responses emphasize the efficiency of financial mechanisms for increasing the resilience of agriculture to drought, e.g., in the form of subsidies for irrigation systems and support for R&D in agriculture. The most prominent impacts of drought on water availability are the decreasing water levels in rivers, lakes and wells and the reduced access to drinking water for households. Respondents voted for options focusing on increasing water storage capacity and promoting water-saving technologies as the most efficient water management measures under drought conditions.

About a third of the responses noticed the impact of drought on health. Examples are more cases associated with thermal discomfort or dehydration, and an increase in respiratory problems due to dust and air pollution. Survey results highlight the access to medical resources and hydration in extreme drought conditions as well as awareness campaigns to prevent dehydration and heat stress as efficient adaptation options.

The most noted drought impacts on the forest and biodiversity sectors were the increase of wildfire risk and tree mortality. The most affected ecosystems were considered to be the wet areas (lakes, rivers, swamps), meadows, and natural agricultural areas. Responses mentioned the degradation of natural habitats and the reduction of the population of some plant and/or animal species as main negative effects of drought on ecosystems. The identified adaptation options for reducing the impact of drought on biodiversity range from restauration of degraded habitats to the implementation of monitoring and intervention programs and to promoting drought-resilient species. Only a low share (7.5%) of the respondents viewed the extension of protected areas as an efficient adaptation option.

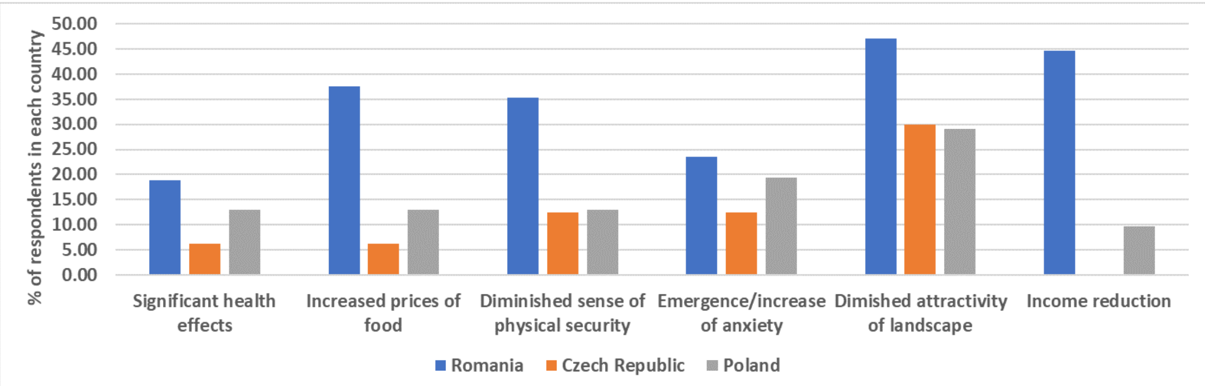
Capabilities Impacted

CSA2_Table1. Description of capabilities impacted by drought hazard.

Capability	Nussbaum´s categories	Functioning	Wellbeing	Relevance	Influenceability	Indicator (qualitative/ quantitative) for measuring capabilities*
Being able to maintain good health	Bodily Health	Basic need for a normal life	Basic needs	Prolonged drought periods are associated with health problems	Accessible healthcare for vulnerable groups	% of survey answers supporting this feature
Being able to be nourished	Bodily Health	Access to sufficient food and income to maintain nutrition and health.	Basic needs	Drought is associated with increased prices and more difficult access/reduced affordability of food products	Policies on financial support	% of survey answers supporting this feature

Being able to move freely from place to place; to be secure against violent assault, including violence;	Bodily Integrity	Safety and security	Basic needs	Drought is associated with increased violence or at least a diminishing feeling of physical safety	Extending research on this impact type, to be able to address the generating factors (e.g., income insecurity)	% of survey answers supporting this feature
Not having one's emotional development blighted by fear and anxiety	Emotions	Basic need for a normal life	Basic needs	Drought is associated with emerging or experiencing anxiety	Accessible mental health support programs	% of survey answers supporting this feature
Being able to enjoy recreational activities	Play	Improved quality of life	Living conditions	Landscape attractivity affected by drought; limitation of opportunities and attractivity of outdoor/nature-based activities.	Sectoral adaptation policies	% of survey answers supporting this feature
Being able to hold property (both land and movable goods)	Control Over One's Environment (Material)	Maintain stable income and living standards under climate stress.	Living conditions	Economic impact of drought may lead to losses of properties	Financial education; policies on financial support	%of survey answers supporting the link between drought and income decrease

We consider the capabilities identified in CSA2-Table1 and assign numeric indicators to them. These measure how much drought impacts the capabilities. We calculate the indicators from the responses to the survey described in section 2.2.4. The preliminary analysis considers for each capability only responses marking a high impact (i.e., 'much' and 'very much') to one survey question. The results presented in CSA2-Figure9 suggest that respondents from Romania perceive higher impacts on the capabilities than those from Poland and from the Czech Republic. In all three countries, responses most prominently emphasize a less attractive landscape and its effect on the ability to enjoy recreational activities. On the opposite side, only a low share of respondents in each of the three countries notices significant health effects in relation to drought.



CSA2_Figure9 Perceived impact of drought on the capabilities, based on responses to the survey disseminated in Romania, Czech Republic and Poland.

2.2.6. Synthesis and Priorities for Action

The results referring to ecosystems indicate that protected areas and broader land systems across the NUTS2 regions remain largely stable or are improving, with degradation generally limited to localized patches. This highlights resilient ecological structures especially in agricultural and forest landscapes. Particularly in parts of Germany and Poland a number of NUTS2 regions display elevated shares of degradation, signaling emerging vulnerabilities. These preliminary findings place a priority on targeted monitoring and management in the regions with higher degradation rates, strengthening early-warning systems, and implementing locally adapted conservation or land-restoration interventions. At the same time, maintaining the positive trends observed in stable and improving regions will require continued support for sustainable land-use practices and long-term ecosystem stewardship.

Stakeholders and individuals perceive the drought hazard as having spill-over effects and, thus, impacting the whole range of socio-economic sectors as well as multiple dimensions at the individual level. Generally, individuals perceive the impact of drought higher in Romania than in Czech Republic and Poland; women and men do equally so. Most respondents from all three countries think that rural populations are highly affected by drought, while urban populations are least affected. The perception of social vulnerability in relation to drought appears to be higher in the selected NUTS2 regions from Romania. The impact of drought on capabilities is perceived more intensely by respondents in Romania. Responses from all three countries suggest that impacts of drought on health are least prominent and that impacts related to recreational activities are most noticeable.

The preliminary analysis suggests that adaptation measures for agriculture to ensure more stable productions and economic income are one direction for action toward reducing the social vulnerability to drought. This would also reduce the perceived high impact on capabilities. Stakeholders' opinions on adaptation options for several sectors indicate directions where more applied research and co-design approaches should concentrate.

2.3. #3 STORM

2.3.1. Summary of Key Risks from D2.2

The objective of CSA 3 is to assess damages from coastal flooding by integrating climate scenarios with damage cost modeling. The analysis placed a significant emphasis on damage cost assessment and socio-economic impacts, specifically including considerations of wellbeing and equity. The analysis projects a severe increase in the economic and human impact of coastal flooding under future climate change scenarios. The methodology employed an integrated analysis approach. This involved using the DTU DamageCost Model (Kaspersen et al, 2025) in conjunction with downscaled climate scenarios (Shared Socio-economic Pathways, or SSPs). Our analysis revealed that Aabenraa is highly sensitive to sea level rise, with flood risks increasing steeply after 2050 in both medium and high climate scenarios. Several sectors will be affected including residential houses, industry, tourism, and agriculture. iCrucially, we quantified a strong negative incidence on equity: large parts of the area affected by a projected high-end flood event in 2100 are currently inhabited by households with relatively low incomes. This severe distributional effect is an argument we use to prioritize adaptation investments in these specific city-centre areas. In contrast, we found that Haderslev's risks increase more gradually over time since a large part of the flood risk areas due to a low altitude are already today facing severe flood risks. While low-income households face flood risks like in Aabenra, the area where they are located is a smaller share of the total flood-risk area compared to Aabenraa. The largest damage costs in Haderslev is on tourism and holiday homes (accounting for 60% of building damage), making the overall equity impacts measured by income of the inhabitants of residential buildings less pronounced than in Aabenraa. Owners by holiday homes however, face large flooding damages in Aabenraa.

CSA3_Table1: Key findings in the CCHs

Feature	Aabenraa Municipality	Haderslev Municipality
Primary Societal Concern	High incidence of equity impact and people at risk.	High total accumulated risk, but equity impact is smaller and growth in exposed population is moderate because primarily holiday homes are at risk.
Vulnerable Location/Group	Low-income households concentrated in the city centre/core areas at risk.	Low-income households are at risk, but the affected area is a smaller share of the total flood-risk zone.
Exposed Population (100-yr Event)	Steep increase projected: 150$ (today) to 2,000–2,300 (by 2100).	Gradual increase projected: 300$ (today), increasing moderately over time.
Dominant Damage Type	Business buildings are the largest single cost, followed by permanent residences (for high storm surge).	Holiday homes (approx. 60% of building damage) and tourism.
Role of Capabilities	Methodology used to capture non-monetary losses like mental stress and lost leisure time due to the burden of managing damages.	Methodology used to ensure adaptation planning accounts for social well-being constraints in addition to asset losses.

Adaptation Priority	Prioritize investment in areas to reduce social inequality due to the concentration of low-income residents in flood zones.	Focus on balancing asset value protection related to holiday homes and tourism with moderate, gradually increasing risk to permanent residences.
CBA Framework	Used equity weights based on diminishing marginal utility of income to adjust flood damage costs upwards for low-income groups.	Used the same equity-adjusted CBA methodology.

2.3.2. Supplementary issues related to D2.2

Socioeconomic data like population, income, age, and education characterize present socio-economic conditions and, thus, offer valuable insights into current exposure and adaptive capacity, and a survey subsequently referred to for the two municipalities displays key information about the impacts on households of floods and flood risks. However, these indicators do not capture dynamic trends or future socio-economic developments that could alter risks and adaptive capacites. The same is the case for future development trends in landuse including settlements, sectoral activities, and other values related to culture and nature.

There is in practice a tradeoff between being able to calculate very context specific flood damages and social impacts in a very detailed way, and the dynamic nature of risk assessments.

2.3.3. Assessment of Societal and Human Vulnerabilities

A. City results of Survey

A survey has been distributed in their official electronic mailbox to all households in Denmark, which are in coastal flooding risks in the areas, where the most recent storm surges happened in 2023 (n=100,000). 18,000 responded and out of them about 700 had flooding in their house. Key survey questions include damage costs compensated by insurance and not compensated, time spend on managing the flood, mental health impacts, expectations to future flooding risks, support from the municipality and emergency units, adaptation measures implemented and wishes to move to other places and sell houses. The survey output is currently linked to a wider range of socioeconomic data in a closed server of Statistics Denmark including age, gender, income, and education. Aabenraa and Haderslev are part of the survey, and the results reveal the tangible human and social burden placed upon residents of Aabenraa and Haderslev by storm flood events. The findings illustrate how these events restrict residents' capabilities (their freedoms and live a life they value) through direct damage, infrastructural failure, and the time and cost of recovery.

Societal Aspects and Capability Constraints in Aabenraa

The Aabenraa survey results are based on responses from 340 individuals with registered residency in the municipality, of whom 273 completed all questions.

1. Direct Impact and Service Constraints

Questionnaire responses identified how storm floods directly impact the core capabilities of Aabenraa residents, particularly concerning mobility and access to central services.

- Direct Damage: 12 respondents reported having water inside their current property, and 31 had water on their property grounds. Crucially, 0 households reported being forced to move to a temporary residence, suggesting that while the events were damaging, the immediate displacement was minimal for the surveyed residents.
- Infrastructure Failure: 28 respondents experienced an interruption in the supply of internet, electricity, heat, or water, restricting the capability to access basic modern necessities and reliable communication.
- Restricted Access (Capability to Mobilize): The most significant restrictions were on access to Roads (126 respondents), the Harbour (118), and the Beach (93). The high restriction of roads and the harbour is a key finding, as it suggests the flood severely restricts the fundamental capability for transport, commerce, and work in the city centre. Furthermore, 64 respondents reported restricted access to daily shops (Dagligvarebutik), significantly impacting the capability to maintain daily life.

2. Recovery Burden and Time Constraints

The time and energy required for recovery place a significant, non-monetary burden on affected households, directly restricting the capability to allocate their time to other aspects of life.

CSA3_Table2: Recovery Burden and Time burden in Aabenraa

Recovery Task	Average Time Burden (Hours)
Preparation before the flood	13.8 hours
Property Restoration (Genopretning af bolig)	45.2 hours
Handling the insurance case	2.6 hours
Garden cleanup	3.2 hours
Non-Work Days Taken	7 days (average holiday/free days)

Funded by the European Union

3. Preparedness and Adaptation Efficacy

The following findings suggest that direct experience drives pro-active adaptation, which is crucial for building resilience capabilities in Aabenraa.

- Information Seeking: 63.6% of respondents who had water *in their current home* sought out information about flood risk, demonstrating that direct experience is the primary driver for seeking information.
- Adaptation Action: The majority (63.6%) of those with water in their current home took active steps to reduce future flood risk (a critical adaptation capability).
- Self-Efficacy: Among those with direct flood experience, 37.5% felt they had an above average ability to limit water entering their home. This reflects a moderate, though not dominant, level of self-efficacy regarding individual flood protection capabilities.
- Post-Flood Information Gap: While pre-flood warning receipt was high (69.6%), a large majority (58%) of those directly impacted did not receive information about what to do after the flood, revealing a major gap in post-event support capabilities.

Societal Aspects and Capability Constraints in Haderslev

The total number of respondents for the questionnaire in Haderslev municipality was 116 (who answered all or part of the survey). Out of that total, 103 individuals answered all the questions.

1. Direct Impact and Capability Constraints

A significant minority of respondents reported direct flood impact, placing a major constraint on their basic capability of having secure shelter.

- Direct Damage: 10 respondents reported having water inside their current property, and 18 had water on their property grounds. The most recent major event was the 2023 storm flood (8 respondents for current property).
- Forced Displacement: 3 households were forced to move to a temporary residence due to the flooding, representing a severe disruption of the capability to maintain a stable home life.
- Infrastructure Failure: 30 respondents (out of 111 total) experienced an interruption in the supply of internet, electricity, heating, gas, or water due to the flood, constraining the capability to access basic modern necessities and services.

Funded by the European Union

- Restricted Access: Floods significantly restricted access to public amenities, most notably roads (46 respondents) and the beach (39 respondents). This directly limits the capability for mobility, work, and leisure. Access to harbour (15), work (6), and daily shops (5) was also compromised.

2. Recovery Burden and Time Constraints

The recovery process places a significant and often non-monetary burden on the affected households, directly restricting the capability to allocate their time and energy to other aspects of life.

CSA3_Table3: Recovery Burden and Time burden in Haderslev

Recovery Task	Average Time Burden (Hours)
Preparation before the flood	114.6 hours
Finding and moving to temporary housing	101.2 hours
Handling the insurance case	128.0 hours
Garden cleanup	163.1 hours
Property restoration (Genopretning af bolig)	271.1 hours

The average time spent on property restoration (271 hours) represents an enormous hidden cost, equating to over 6 full-time weeks (considering 40-hour weeks) of non-paid labor, directly limiting the capabilities of affected residents.

3. Preparedness and Information Gaps

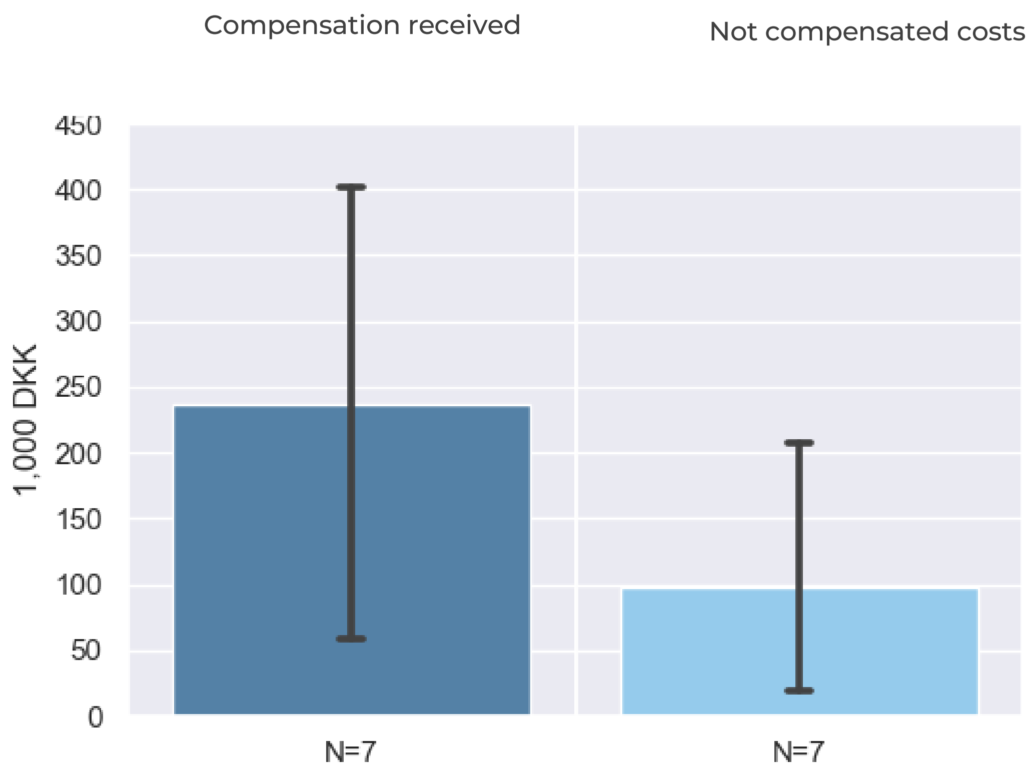
The survey highlights a disparity in preparedness and information access based on direct experience, impacting the capability to act autonomously in the face of risk.

- Risk Information Seeking: Only 35.1% of respondents who had water on their property (but not in the home) actively sought information about flood risk. However, this rises sharply to 69.8% among those who had water *in their current home*, demonstrating that direct experience is the primary driver for seeking information.
- Information Sources: The main sources for seeking risk information were the Municipality (54%) and the Environmental Agency/Coastal Directorate (48%).

- Warning Systems: The majority of respondents who experienced a direct impact (76.7%) received a warning *before* the flood occurred. However, a significant gap exists in post-event support: 69.8% of those with water in their home did not receive information about what to do *after* the flood.
- Self-Efficacy: While nearly half (48.8%) of those with water in their current home took action to reduce risk, only 34.9% of this group felt they had above average ability to limit the amount of water entering their home. This suggests a potential gap between taking action and feeling truly empowered (the capability to effectively adapt).

CSA3_Figure1 provides a summary of the financial burden and compensation received by Haderslev residents whose current homes experienced storm flood damage. Specifically, it illustrates two key metrics using bar charts with 95% confidence intervals:

1. Compensation Received from insurance: The average amount paid out (approx. 240, 000 DKK) by the Danish public financial schemes (Naturskaderådet/Stormrådet).
2. Not compensated Costs: The average amount (approx. 100, 000 DKK) the affected households had to pay themselves to cover the cost of repairs and damages.



CSA3_Figure1: Financial burden and compensation received by Haderslev residents

In conclusion, our comparative analysis reveals that while both municipalities are vulnerable, the nature of the capability constraint is fundamentally different. Aabenraa's challenge lies in managing economic and functional risk concentrated in its low-income city core, where projected future risks are steep, yet individual recovery burdens were low. This i.e. reflect that Aabenraa has experienced several floods, and that the municipality and emergency units have been very active in coping with the risks and managing the disaster. Haderslev, conversely, faces flooding in a holiday homes remote from the city centre, where it primarily is the responsibility of local owners to take care of their own property during the flooding. This has played a role in the high recovery time burden and displacement rate, indicating a heavier toll on long-term household well-being and capability. Crucially, in both areas, the survey identifies a clear target for systemic adaptation: the major gap in official post-event information and guidance represents a shared institutional failure that must be addressed to enhance overall community resilience.

CSA3_Table4: Comparison between the two CCHs

Area of Difference	Aabenraa (N=340)	Haderslev (N=116)	Key Conclusion
Recovery Time Burden	Substantially Low (Average 45.2 hours for property restoration).	Substantially High (Average 271.1 hours for property restoration).	Our data suggests flood damage was less structurally severe for Aabenraa's residents, resulting in a lighter long-term capability constraint. Haderslev had a large number of individual summerhouses flooded, where it was the responsibility of the private owner to handle the case, while flooded houses in Aabenraa primarily was city houses
Immediate Impact (Displacement)	0 households forced to move to temporary housing.	3 households forced to move to temporary housing.	Haderslev faced a higher immediate risk to the basic capability of secure shelter.
Nature of Access Constraint	High restriction on Roads (126) and Harbour (118) access.	High restriction on Roads (46) and Beach (39) access.	Aabenraa's primary constraint is economic and functional (commerce, city core); Haderslev's is more leisure and mobility-based.
Pro-Active Adaptation	Higher rate of action: 63.6% of	Lower rate of action: 48.8% of	Aabenraa showed greater individual resilience and efficacy post-experience.

	affected took steps to reduce risk.	affected took steps to reduce risk.	
Systemic Support Gap	58% received No post-flood information.	69.8% received No post-flood information.	Both municipalities share a major failure in official post-event guidance and support capabilities.

Capabilities Impacted

Building on the theoretical foundations of Amartya Sen's Capability Approach and Martha Nussbaum's ten central human capabilities (Nussbaum 2013; 2003)., we have identified a specific set of capabilities that are critically impacted by flood risk (CSA3_AnnexTable1). This approach allows us to move beyond measuring infrastructure damage to measuring the actual reduction in human well-being and freedom within the CCHs.

The assessment focuses on how physical flood events translate into social impacts across several key dimensions:

- Life, Bodily Health, and Integrity: Flooding directly threatens physical safety and long-term health. Beyond the immediate risk of injury, we account for the preservation of mental health, which is often compromised by the trauma of displacement and property loss.
- Senses, Imagination, and Thought: We identify the loss of access to educational and cultural spaces when schools or community centers are flooded, which restricts the "literacy and basic mathematical and scientific training" necessary for a dignified life.
- Practical Reason and Affiliation: Flood risk often disrupts the ability to engage in critical reflection and community planning. Our analysis evaluates how institutional trust and participatory planning act as levers to protect these capabilities, ensuring individuals can maintain social networks and "live with and toward others" even during crises.
- Control Over One's Environment: This is a critical category in our analysis, encompassing both political (participation in flood-mitigation choices) and material rights. It includes the ability to hold property, access safe housing, and maintain stable work opportunities and income in flood-prone areas.

For each of these categories, we qualitatively described the specific flood-related impacts and identified potential policy intervention levers. These range from physical measures, such as flood-resilient infrastructure and retrofitting, to social support systems, including emergency schemes, institutional trust-building, and participatory planning.

To ensure the framework is actionable, we have associated these impacts with indicative indicators. These include quantitative metrics, such as the share of the flooded road network (impacting mobility and health access), and qualitative measures, such as self-reported levels of institutional trust and the share of residents experiencing work interruption. This systematic mapping ensures that recovery efforts and adaptation investments are targeted toward restoring the most essential human freedoms.

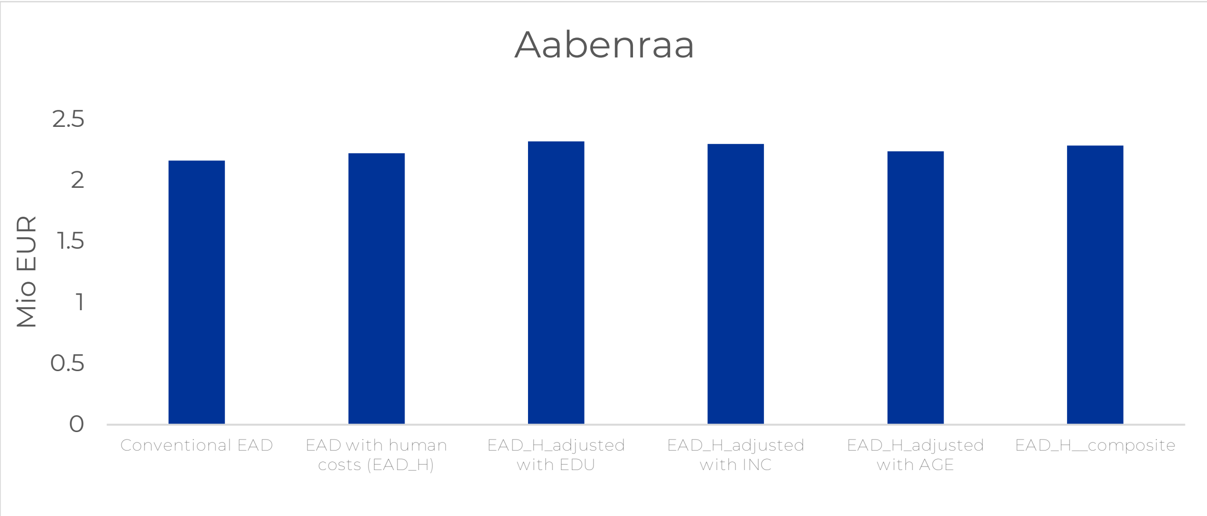
This theoretical mapping of capabilities to specific indicators provides the necessary foundation for translating abstract well-being into measurable socio-economic data. By applying this framework to specific geographical contexts, we move from a general understanding of vulnerability to a precise quantification of how climate hazards degrade the quality of life for different social groups.

Our analysis of coastal flood risk within the CSA 3 STORM hotspots (Aabenraa and Haderslev) utilizes a human-centered approach that goes beyond the conventional Expected Annual Damage (EAD) assessments. Standard EAD models quantify direct monetary losses to buildings and infrastructure but inherently fail to account for the crucial non-market costs and social distribution of vulnerability. To address this gap, we applied a novel methodology, time cost, that integrates costs related to human impacts in the DTU Damagecost model (Kaspersen et al., 2025; Halsnæs et al., 2020). We also adjusted flood burdens based on pre-existing socio-economic factors (proxy for vulnerability)—specifically age, income, and education level to understand how flood burden increases with pre-existing capabilities/ vulnerabilities (Shepherd & Dissart, 2022). These adjustments are done using log-log regression and elasticity estimates.

The integration of social impacts in our study areas involves two stages that increase the assessed risk above the conventional EAD baseline

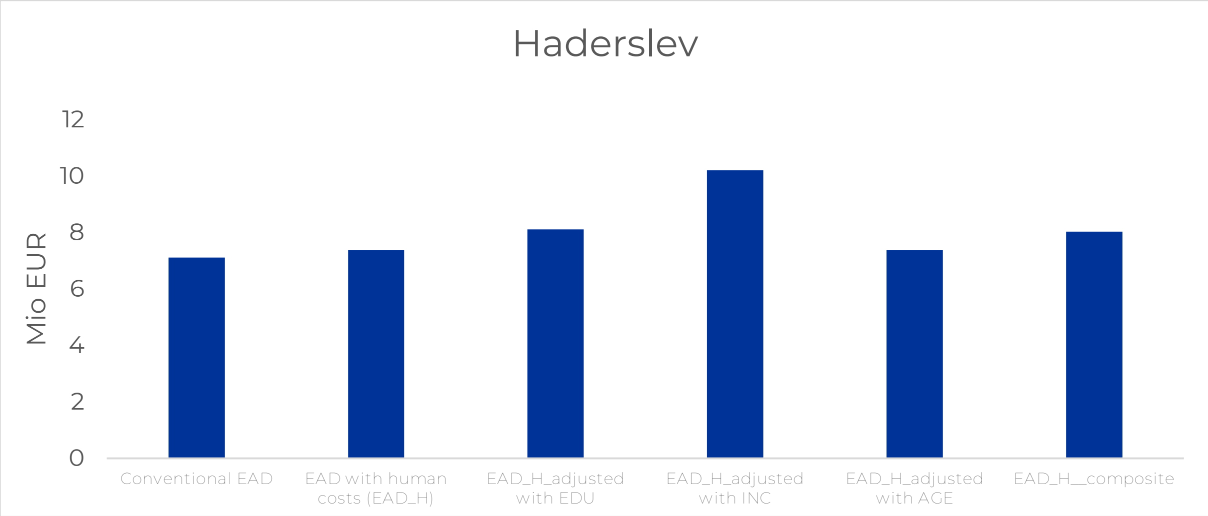
a. The addition of human-centred costs (using tables CSA3_Tables 2 and 3) (Halsnæs et al., 2024)
b. Adjusting for socio-economic vulnerability (EDU: level of education; INC: per capita income; AGE: children and older population)

The analysis for Aabenraa municipality (CSA3_Figure2) shows that with conventional Expected Annual Damage (EAD) losses in 2024 are approximately 2.16 Mio EUR and including human related costs increases the total flood burden to approximately 2.22 Mio EUR. This difference represents an essential addition to the total damage, confirming that human-centered impacts lead to a measurable underestimation of the true flood risk, even before accounting for socio-demographic variations. This represents a 5.6% increase in the assessed flood burden over the initial EAD baseline, demonstrating the impact of Aabenraa's specific vulnerabilities. Analysis of the individual socio-demographic vulnerability factors shows that vulnerability related to education level is the strongest single driver of the inequality flood burden, resulting in the highest adjusted cost (approximately 2.32 Mio EUR). This is closely followed by the adjustment for per capita income, which raises the burden to approximately 2.30 Mio EUR. The adjustment for vulnerability related to age (children and elderly population) contributes to a smaller, yet notable, increase, raising the cost to approximately 2.24 Mio EUR. The overall integrated cost (2.28 Mio EUR) provides the most comprehensive measure for future adaptation planning and resource prioritization in Aabenraa.



CSA3_Figure 2: Flood burden including human related costs and socio-econ vulnerability in Aabenraa

The analysis for Haderslev municipality (CSA3_Figure3) shows that the conventional Expected Annual Damage (EAD) is approximately 7.2 Mio EUR. Including human related costs increases the total flood burden to approximately 7.5 Mio EUR. This difference represents an essential addition to the total damage of 0.3 Mio EUR, confirming that by ignoring human-centered impacts lead to an underestimation of the true flood risk by approximately 4.2%. Adjusting these costs due to the municipality's pre-existing social conditions shows that vulnerability related to per capita income is the largest single driver of this inequality burden, resulting in the highest adjusted cost (approximately 10.2 Mio EUR). This suggests that Haderslev's income profile is low relative to the national average which significantly amplifies the impact of floods. The adjustment for education level also shows a strong amplifying effect, raising the cost to approximately 8.1 Mio EUR. The final integrated cost is approximately 8.0 Mio EUR. This total represents an 11.1% increase in the assessed flood burden over the initial EAD baseline, demonstrating the pronounced impact of Haderslev's specific socio-demographic vulnerabilities.



CSA3_Figure3: Flood burden including human related costs and socio-econ vulnerability in Haderslev

2.3.4. Synthesis and Priorities for Action and Stakeholder Engagement

The entire assessment for Aabenraa and Haderslev is based on a long-term collaboration with local stakeholders, where partnerships with the municipality in Aabenraa has been going on for about 8 years and in a shorter period with Haderslev. Aabenraa has played a key role in the development of the damage cost model, which is used in the current study, and the model has played an import role in local risk studies and adaptation planning for the municipality. Several stakeholders have been involved in the process including the business sector representing the harbour area, the emergency units, and the educational institutions. The current study has particularly included dialogues with the technical staff of the municipality, where they have highlighted a particular need for further support to assess adaptation projects in relation to flooding from streams inland, adaptation of a stream running out in the harbour area including establishment of green areas, and adaptation of a beach area south of Aabenraa harbour. Another key issue is to get support to communication and awareness raising with local citizens, and the survey referred to previously is adding important information to this. Haderslev is in an earlier stage of adaptation planning than Aabenraa, and there is a need for support to a comprehensive mapping of flooding risks and adaptation options, which was highlighted in a meeting with municipal staff from the planning and adaptation units. A dialogue has also been conducted with local citizens affected and a local ferry captain at flooding sites, which revealed a strong demand for fast initiatives from the municipality. All together, it has in Haderslev been emphasized that there is a need for being able very fast to implement a coastal protection project in a beach area. This project is already planned, but conflict about burden sharing at present is a large barrier for moving forward. The issue is primarily about how much local property owners should pay for the adaptation project, and to which extent the municipality should contribute. The CARMINE CSA will here support the local society with evidence based information about how much the flooding risks can be reduced by the project and about who is gaining from the project in terms of private and public utility.

2.4. #4 FLOOD

2.4.1. Summary of Key Risks from D2.2

The CS4 focuses on the increasing flood and flash flood risk in the valley areas of Trentino-Alto Adige, a region identified as a Climate Change Hotspot (CCH) due to the combined effect of physical and socio-economic vulnerability under changing climate conditions. An integrated assessment framework was applied, combining high-resolution climate and hydrological simulations with stated preference methods to monetise the societal benefits of mitigation and adaptation (M&A) strategies under alternative impact scenarios. The analysis estimated that the total societal benefits of implementing M&As amount to approximately €135 million per year under mid-century conditions (2041–2050), and over €175 million per year by the end of the century (2090–2099). These figures represent the upper bound of socially acceptable investment in flood prevention and adaptation. Moreover, disaggregated results by income and gender revealed differences in stated preferences, underlining the relevance of integrating distributional concerns into flood risk policy design, ensuring that adaptation strategies remain socially inclusive.

2.4.2. Supplementary issues related to D2.2

Although the assessment conducted in D2.2 provided a robust foundation for evaluating the socioeconomic benefits of M&A strategies, it did not address how individuals and communities interpret and respond to flood risk. A central gap concerns the lack of attention to local resilience, understood here as the capacity of a territorial system (not only individuals, but institutions and social networks) to anticipate, absorb, and recover from disasters (Cutter et al., 2008; IPCC, 2022). We address here this gap by presenting empirical results on the behavioural and institutional factors that condition local resilience to flood risk. The analysis builds on survey data collected through a structured questionnaire. The survey was administered online between January and March 2025 to a representative sample of 2,000 residents of the Triveneto area (North-Eastern Italy), using quota sampling to ensure balance in terms of gender, age, education and income. Data collection was carried out by a professional survey agency

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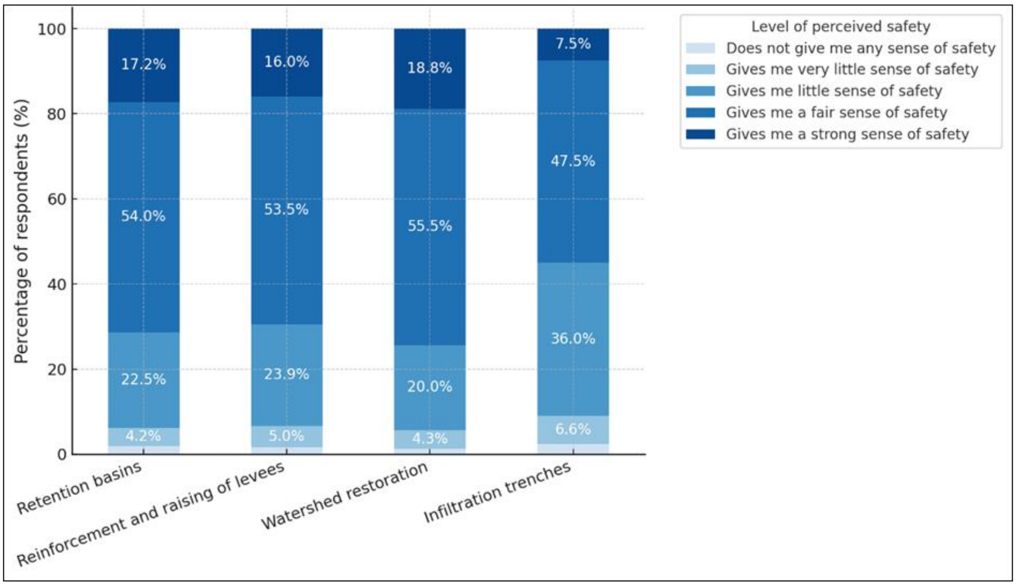
and received ethical approval from the Departmental Ethics Committee of the TESAF Department at the University of Padova. The questionnaire's architecture was introduced and detailed in D2.2. Selected findings are presented in the sections below, while additional results are reported in CSA2 Annex.

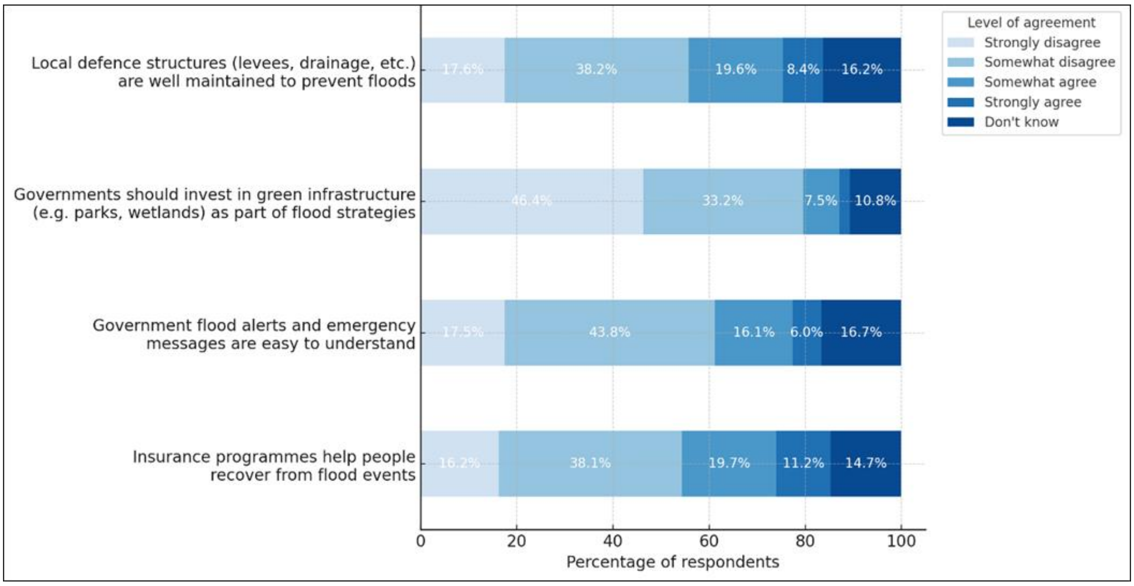
Public perceptions of mitigation and adaptation strategies

A dedicated section of the questionnaire explored how the general public perceives different strategies and instruments used in flood risk management. Figure 1 shows the perceived safety of four commonly adopted measures. Before responding, participants were provided with standardised descriptions to ensure a shared understanding of each measure's purpose and function. More than 70% of respondents expressed moderate-to-high perceived safety for watershed restoration, levees, and retention basins, suggesting broad public trust in these interventions. By contrast, infiltration trenches received more cautious evaluations. These findings point to relevant differences in how protective measures are perceived, which may influence the social acceptability and uptake of certain Nature-Based Solutions (NBS).



CSA4_Figure1: Perceived safety of protective measures.

Figure 2 further explores public perceptions by presenting levels of agreement with a set of items related to key aspects of flood risk management. Perceptions are most critical with respect to the maintenance of local flood defence structures (e.g. levees, drainage systems), with responses indicating limited trust in the upkeep of these measures. Perceptions of green infrastructure (e.g. parks, wetlands) are mixed and tend towards disagreement: more respondents question the importance of investing in these measures than support it, and a non-negligible share remains uncertain, suggesting that public support for NBS as part of flood strategies is still fragile. Flood alerts and emergency communication are widely perceived as difficult to understand, highlighting weaknesses in how early warnings and guidance are framed and disseminated. Perceptions of insurance programmes are similarly divided, indicating possible gaps in the accessibility of, or awareness about, financial risk-sharing mechanisms.



CSA4_Figure2: Perceived effectiveness of measures for flood risk management.

Citizen trust and perceptions of public authorities for flood governance

In the survey, respondents were asked to indicate their level of trust in different institutional actors involved in flood risk management. Results are illustrated in Figure 3. The results suggest a differentiated trust structure: trust appears to be stronger when institutional actors are perceived as closer to the community or directly involved in emergency response, while more distant or politicised institutions are met with greater scepticism.

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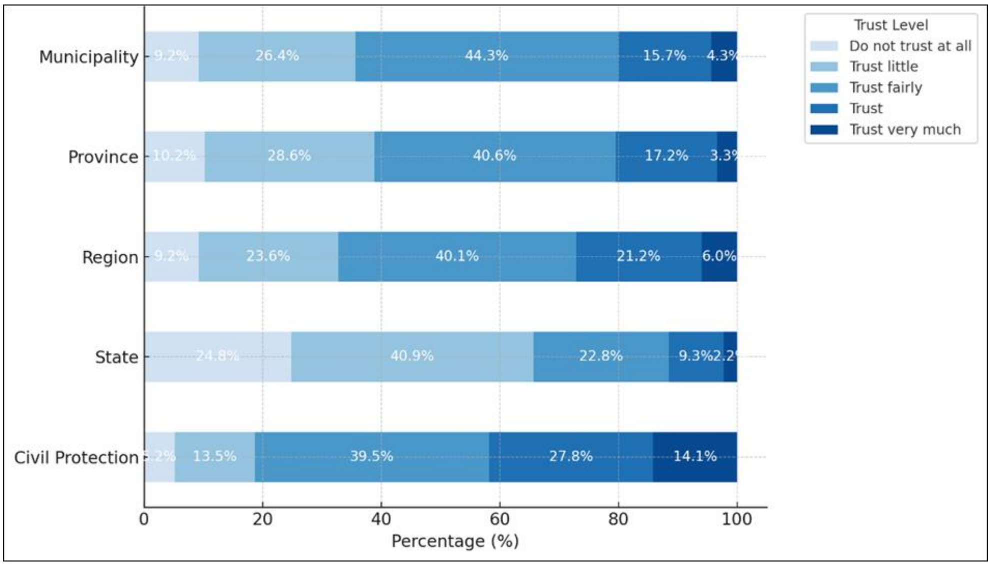
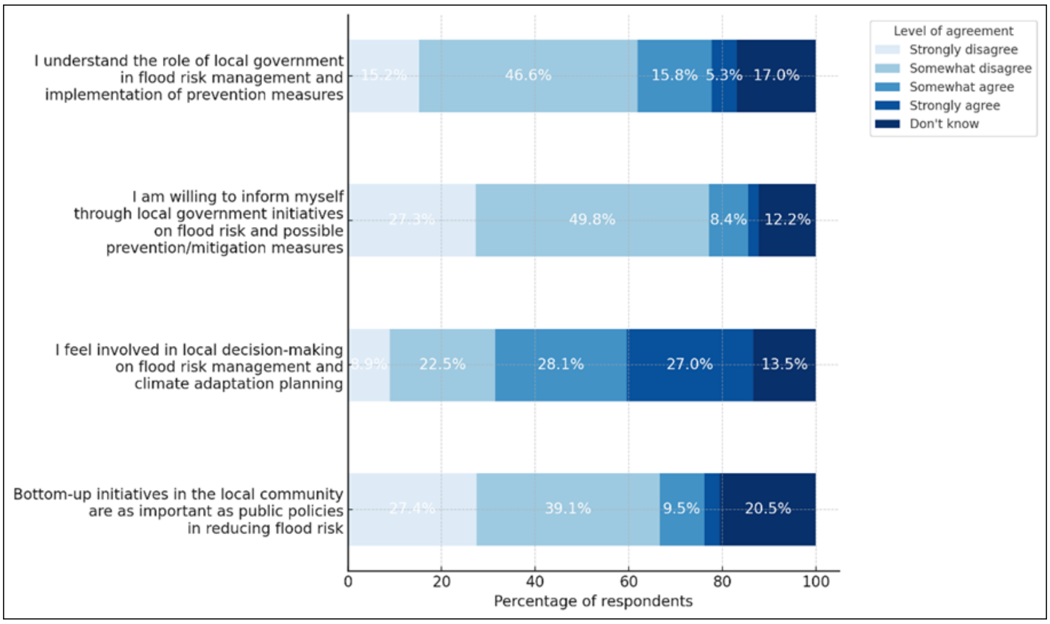


CSA4_Figure3: Trust in Institutions for flood management.

To further explore the relationship between trust and institutional proximity, Figure 4 reports responses to survey items on perceptions of local flood risk governance and adaptation planning. Despite relatively favourable trust in local institutions, only a small minority of respondents report a clear understanding of the role of local authorities in flood prevention and management. Willingness to engage with institutional information is likewise limited, possibly confirming a lack of trust in the institutions delivering them. However, this reluctance to engage is not fully mirrored in perceptions of inclusion: over half of respondents express some agreement with being involved in local decision-making on flood governance and adaptation. This tension may help explain the ambivalence observed in the final item on the importance of bottom-up community initiatives: only 12.9% agree with the statement indicating that community-based action is not widely recognised as a relevant complement to public policy in this context.

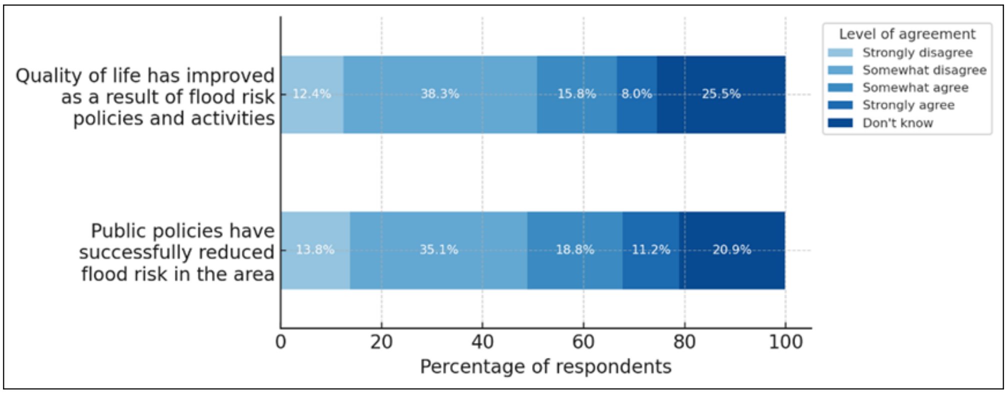


CSA4_Figure4: Public perception of local governance for flood management.

These findings portray a fragmented relationship between local institutions and citizens in the context of flood risk governance. Trust in municipal and regional authorities is comparatively higher than for national actors, this does not translate into a clear understanding of their institutional mandate, nor into a strong willingness to engage with their information efforts. The relatively high proportion of respondents who report feeling involved in local decision-making suggests that participatory structures may be in place, yet their visibility, inclusiveness, or effectiveness appear insufficient. Moreover, the limited recognition of bottom-up initiatives as relevant complements to formal policy points to a persistent gap in civic engagement.

Perceived effectiveness of flood risk policy

The survey included two items exploring perceived effectiveness and benefits in terms of local quality of life of flood risk management policy. Results are illustrated in Figure 5. Public confidence in the effectiveness of flood-related policies remains limited. The results may reflect both the perceived persistence of local flood-related vulnerabilities and a lack of visibility or attribution of positive outcomes to specific policy measures. They also indicate that the legitimacy of flood governance efforts remains fragile, and that demonstrating tangible benefits to local communities, both in terms of safety and well-being, may be essential to foster trust and public support.



CSA4_Figure5: Public perception of flood risk policy.

2.4.3. Ecosystem aspects in results

Survey responses suggest that part of the population considers ecosystem-related factors when evaluating flood risk, including both its causes and the effectiveness of mitigation and adaptation strategies. Respondents recognise not only climatic drivers but also human-induced pressures, such as riverbed alteration and urbanisation, as contributors to local vulnerability, pointing to an awareness of degraded ecosystem services (CSA2 Annex Figure 4). Perceptions of protective measures indicates that while large-scale interventions like watershed restoration are generally trusted, less visible options like infiltration trenches receive more sceptical evaluations (Figure 1). Views on green infrastructure investment remain mixed, indicating that residents' support for ecosystem-based approaches is still limited (Figure 2). By contrast, stakeholder perspectives show greater alignment around the relevance of NBS (see section 2.4.4). Further detailed considerations and supporting evidence are discussed in CSA2 Annex.

2.4.4. Assessment of Societal and Human Vulnerabilities

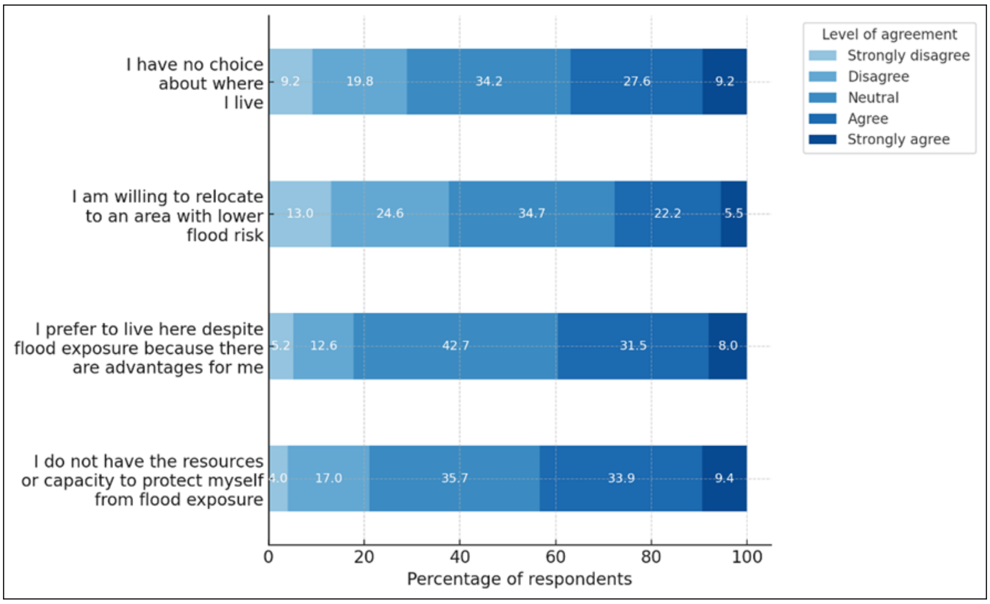
Insights from resident survey data

A first empirical insight into social vulnerability is provided by the assessment of flood impacts. The survey included a targeted question, administered exclusively to respondents who had previously experienced at least one flood episode (see CSA4 Annex), asking them to indicate the types of damage they had personally suffered. The objective was to capture the diversity of flood-related impacts and identify the most prevalent forms of individual and household sensitivity. Results are summarised in Table 1. Among affected individuals, the most frequently reported impact concerns psychological stress, followed by damage to housing structures and the loss of personal belongings. The prominence of non-material consequences underscores that the effects of flooding are not limited to physical damage but also involve emotional and psychological dimensions. In addition, a considerable share of respondents reported disruptions to their work or professional activities, confirming that flood events affect both residential and economic domains.

CSA4_Table1: Incidence of flood damage among respondents who experienced flood.

	Respondents reporting damage (%)
Damage to the home (e.g. roof, walls, windows)	30.18
Damage to personal belongings (e.g. furniture, appliances, valuables)	27.45
Damage to personal vehicles	20.87
Damage to agricultural or forest property (e.g. garden, trees, smallholding)	20.06
Work interruption or loss of income	19.74
Health problems (e.g. injury or flood-related illness)	2.25
Psychological stress	37.24
No damage reported	26.65

To assess perceptions of adaptive capacity and constraints, the survey included four items on self-protection, willingness to relocate, and attachment to place (Figure 6). Over 36% agreed they have no choice about where they live, suggesting structural constraints on residential mobility and the possible presence of trapped populations. Willingness to relocate was more polarised: 28% would consider moving to a safer area, while a similar share disagreed. Around 40% preferred to stay despite flood risk, indicating place attachment or a perceived balance of risks and benefits. Finally, 43% expressed limited capacity to protect themselves from flooding, pointing to widespread perceived constraints on individual preparedness.



CSA4_Figure6: Perceived ability and willingness to adapt residential location to flood risk.

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Qualitative Findings from Stakeholder Engagement

The CSA4 stakeholder workshop, held on 27 March 2024, brought together eight representatives from key regional organisations, including water utilities, environmental agencies, regional administrations, infrastructure management bodies, and protected areas. Participants were invited to discuss the current and anticipated impacts of climate change and flood risk in their respective sectors, and to identify critical gaps relevant to adaptation planning.

Concerning the manifestations of vulnerability, representatives of regional environmental monitoring and protection agencies emphasised that climate-related pressures bring implications for crucial economic sectors such as agriculture, manufacturing, and local ecosystems. Stakeholders from the water management sector stressed the increasing exposure of water supply and purification systems to flood-related hazards and the cascading effects these events can generate across interconnected sectors. Recent floods and flash floods were reported to have temporarily compromised purification plants in mountain areas of north-eastern Italy, causing service interruptions that affected both residential and industrial users. These disruptions exposed the fragility of critical infrastructure and highlighted interdependencies with other sectors that depend on stable water provision. Participants also noted that extreme precipitation and surface water overflow increase microbiological contamination risks, posing growing challenges to drinking-water quality and safety. institutional actors involved in hydrographic and basin management described how climate-induced changes in rainfall patterns and flood dynamics are already affecting the design and maintenance of hydraulic works and the adequacy of current planning instruments, particularly in relation to urban development. They pointed out that current regulations do not explicitly require the consideration of future climatic conditions in planning and design, resulting in a mismatch between observed risk evolution and existing standards. This gap was seen as a barrier to proactive adaptation.

In the tourism sector, stakeholders noted that flood risk represents an emerging challenge for regional destinations, generating both physical damage and operational disruption. Extreme events were reported to affect transport networks and tourism facilities, particularly in mountain areas where accessibility is crucial for local economies. Evidence from the "Dolomiti Bellunesi" National Park further confirmed the vulnerability of tourism infrastructure, recalling the damage caused by events such as the Vaia storm, which led to the loss of a visitor centre and the degradation of trails and recreational areas. Moreover, participants stressed that climate-related hazards affect not only tourism infrastructure but also the ecological balance of mountain ecosystems, altering species distribution and reducing habitat suitability.

In addition to highlighting sector-specific vulnerabilities, stakeholders identified a number of enabling conditions that are critical to reducing exposure and sensitivity, and to enhancing adaptive capacity at both institutional and territorial levels. First, they emphasised the need to overcome fragmented responsibilities by strengthening institutional coordination. In particular, the discussion highlighted how addressing hydro-geological risk under climate change requires better integration across civil protection, soil protection, and spatial planning functions. Participants pointed to the importance of coordinated approaches supported by shared decision-making tools, as a foundation for evidence-based planning and targeted adaptation measures. Stakeholders also stressed the value of aligning flood risk governance with land management and tourism planning, especially in areas where economic relevance and environmental vulnerabilities intersect. In terms of M&As, river renaturation and ecosystem restoration were identified as priority options to address the combined effects of hydrological hazards and ecological degradation, with potential co-benefits for both risk reduction and biodiversity conservation.

Capabilities Impacted

Building on Sen's Capability Approach and Nussbaum's categories, we identified a set of key capabilities that are affected by flood risk in the CCH and are relevant for assessing societal and human vulnerability. The full list is provided in CSA4 Annex Table 1. The capabilities considered cover both basic needs and living conditions. They include the ability to move freely and access essential services, to live in safe housing, to preserve physical and mental health, and to work under safe and stable conditions. They also encompass the capacity to maintain work opportunities and income in flood-prone areas, and to rely on trustworthy institutions that provide effective protection and support. For each capability, we qualitatively described the main flood-related impacts, identified potential levers for policy intervention (e.g. flood-resilient infrastructure, nature-based solutions, relocation and retrofitting measures, emergency support schemes, improved communication and participatory planning), and associated indicative quantitative or qualitative indicators (e.g. share of flooded road network, share of residents reporting damage to their home or work interruption, levels of institutional trust).

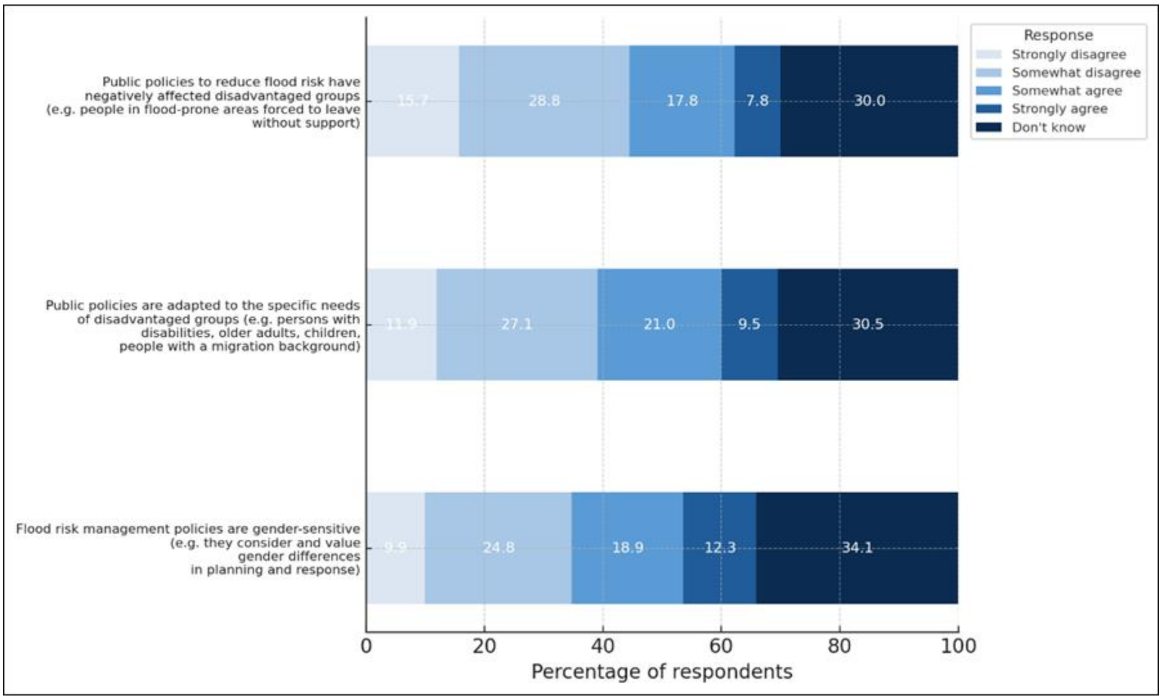
2.4.5. Gender and social inclusion Dimensions

The aim of this section is to assess whether flood-related vulnerabilities in the CCH area vary by gender, economic conditions and age, with particular attention to older adults. To this end, the flood-related impacts and adaptive capacities identified at population level (Section 2.4.4) were disaggregated along these dimensions.

CSA4 Annex Table 2 reports the share of respondents in each gender, age and income group who experienced different types of flood-related damage. Several statistically significant differences emerged. Women reported psychological stress more frequently than men, whereas men were more likely to report no damage. Respondents aged 65 or older were significantly more likely to report damage to agricultural or forest property and less likely to report no damage. With respect to economic status, respondents in the medium-income group were among the least likely to report having experienced no damage, whereas both low- and high-income respondents reported substantially higher shares. This suggests that both groups may have been affected by flood-related impacts not fully captured by the predefined damage categories included in the questionnaire.

CSA4 Annex Table 3 reports mean levels of agreement (5-point Likert scale) with four items on individual attitudes and perceived constraints related to flood exposure, disaggregated by gender, age group and income. No statistically significant differences emerged by gender, indicating broadly similar perceptions of adaptive capacity and constraints. By contrast, age and income are clearly associated with variation in responses. Younger respondents are significantly more likely to agree that they have no choice about where they live and report lower perceived capacity to protect themselves from flooding, whereas older respondents express higher perceived control and preparedness. Economic conditions show a similar pattern: low-income respondents report the highest agreement with having no choice about where they live and are more likely to indicate a lack of resources for self-protection than high-income respondents.

Finally, the survey also included three items on perceptions of equity and inclusion in flood risk governance, focusing on: (i) potential negative effects on disadvantaged groups; (ii) adaptation of policies to specific social needs; and (iii) sensitivity to gender. Respondents answered on a five-point Likert scale, with a “don’t know” option to capture uncertainty. As shown in Figure 7, responses reveal mixed and often uncertain perceptions. Across all items, agreement and disagreement were relatively balanced, but around 30% of respondents selected “don’t know”, indicating limited awareness or confidence in assessing the social and gender dimensions of current flood policies. These findings point to a low public visibility of equity-related considerations, rather than outright criticism.



CSA4_Figure7: Perceived equity and inclusiveness of flood-related public policies.

2.4.6. Synthesis and Priorities for Action

The current analysis presents a multidimensional picture of flood-related vulnerability in the CCH, shaped by the interaction of social, institutional, and environmental factors. Drawing on both quantitative and qualitative evidence, a number of cross-cutting patterns emerge that underscore the structural constraints affecting adaptive capacity at individual and systemic levels.

First, the analysis reveals widespread limitations in individual preparedness. A substantial share of respondents report lacking the resources or capacity to protect themselves, and many perceive no real choice over their place of residence. These constraints are more frequently reported by younger and lower-income individuals, indicating that adaptive capacity is unequally distributed across the population. The issue of "trapped" populations, individuals aware of the risk but unable to respond effectively, appears relevant in this context. Furthermore, psychological stress is the most frequently reported impact among those previously affected by flooding, pointing to the relevance of non-material dimensions of vulnerability. Disaggregated results highlight additional disparities: women are more likely to report emotional distress, and lower-income groups are less confident in their ability to cope or relocate. In this sense, adaptation strategies should account for the differentiated capacities and constraints across social groups. Policies must be designed and evaluated through an equity lens, ensuring that social inclusion and psychological well-being are integral components of flood risk management.

Second, governance-related dimensions emerge as critical in shaping both perceived vulnerability and public trust. Local and regional institutions are generally viewed more favourably than national actors, however citizens express limited understanding of institutional responsibilities and low confidence in flood-related policies. Residents believe that current policy strategies have poorly contributed to improving quality of life. Bottom-up participation also appears constrained: although some respondents feel involved in local decision-making and community-based initiatives receive little recognition. These findings point to a fragmented and low-visibility governance landscape, where participatory mechanisms lack credibility, and where public engagement remains partial. Notably, many respondents are uncertain about the social fairness of current policies, with a high proportion unable to assess whether equity or gender considerations are adequately addressed. In response, it is essential to enhance the transparency of governance processes and improve the clarity of risk communication. Public trust and willingness to engage depend not only on access to information, but also on the awareness and perceived fairness of institutional action.

Stakeholder perspectives confirm and complement these findings reporting increasing exposure to flood risk and highlighting vulnerabilities across critical infrastructure and essential services. However, the institutional response remains hampered by a lack of integration between policy domains. Current planning instruments are often based on outdated risk assumptions and fail to incorporate projected climate dynamics. This misalignment limits the capacity of public institutions to develop forward-looking adaptation strategies. Stakeholders underscore the need for enhanced institutional coordination, improved data sharing, and the development of co-produced planning tools. Particular attention is drawn to the alignment of flood risk management with land use and productive sectors, especially in areas where environmental and economic vulnerabilities intersect. Reducing systemic exposure requires improved coordination across institutional levels.

2.5. #5 SNOW

2.5.1. Summary of Key Risks from D2.2

The CS5 (snow) assessment under CROSSEU D2.2 examined how climate change is reshaping snow-avalanche hazards and socioeconomic vulnerability in the European Alps and Carpathian Mountains. Using climate indicators, terrain and forest susceptibility, and NUTS3-level exposure data for tourism, transport, and forestry, the analysis mapped the evolving risk landscape across both regions.

The Alps. Projections indicate more frequent rain-on-snow events and an increase in wet-snow avalanches, while dry avalanches decline with reduced cold-season snowfall. Under RCP8.5, wet-snow activity intensifies at higher elevations, and rising snowpack instability may also heighten related slope hazards. High tourism density, extensive infrastructure, and growing valley populations make regions such as Savoie, Valais, Tirol, and Graubünden among the most exposed in Europe. Tourism and transport networks face recurrent disruptions, and mid-elevation protection forests experience growing stress. Despite strong adaptive capacity, continued updates of hazard maps, slope stabilization, and climate-informed planning remain essential.

The Carpathians. Overall hazard is lower, but localized vulnerabilities are significant. Wet-snow avalanche potential increases moderately, while dry avalanches decline. Depopulation reduces exposure, yet hotspots such as Nowotarski (PL) and Žilinský kraj (SK) face rising risk due to expanding winter tourism and limited early-warning capacity. Tourism impacts are uneven, transport routes in southern Poland and northern Romania remain sensitive even to small avalanches, and forestry faces moderate exposure. Socioeconomic vulnerability is amplified by limited governance, weak coordination, and constrained financial resources; population decline can also weaken response capacity. Strengthening early-warning systems, improving risk mapping, and enhancing cross-sector cooperation are key priorities for building resilience to evolving snow-related hazards.

2.5.2. Supplementary issues related to D2.2

The seven snow-avalanche storyline events across the Alps and Carpathians show that avalanche impacts extend well beyond physical damage, affecting socioeconomic sectors and institutional systems. However, gaps in event documentation, indirect-impact reporting, and institutional vulnerability data limit the completeness of current assessments. The storylines reveal that impacts on tourism, forestry, and transport, which are sectors highly sensitive to disruption, are often unrecorded or underestimated. Institutional response capacity also differs markedly: Alpine countries operate coordinated systems increasingly challenged by compound events (e.g., rain-on-snow, rapid thaw), while Carpathian authorities remain largely reactive due to less robust governance and limited preparedness.

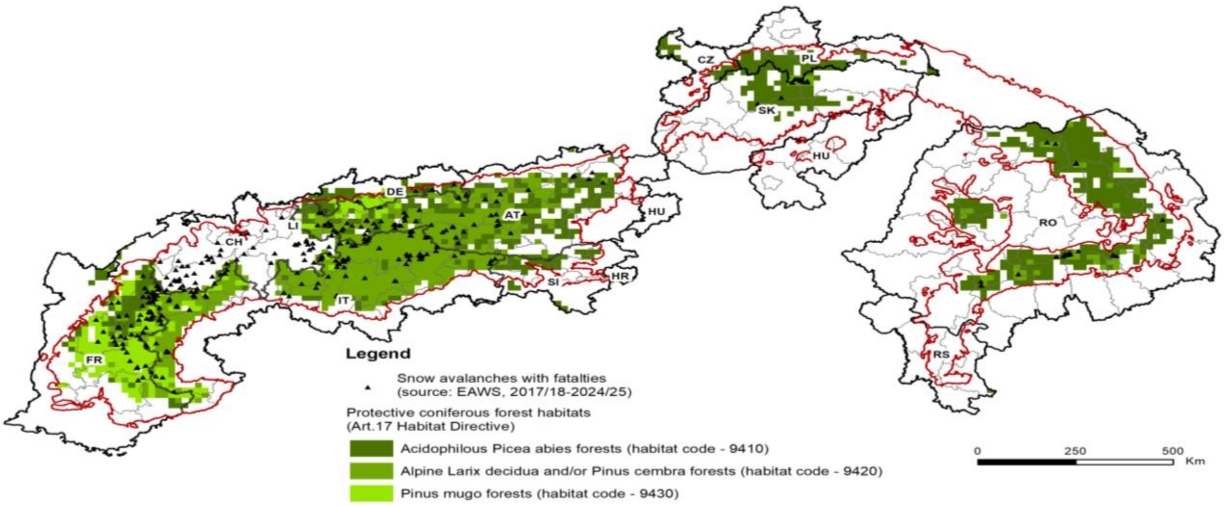
The vulnerability analysis relied on physical and socioeconomic indicators and did not integrate observed event impacts, leaving out indirect and intangible effects such as community isolation, tourism losses, and psychological stress. Limited data sharing between local administrations and private operators further restricts harmonized European-level assessments. A systematic, harmonized data framework is needed, including sector-specific impact indicators, institutional capacity metrics, and compound hazard interactions.

Persistent data fragmentation, especially in the Carpathians and eastern Alpine regions, hampers accurate evaluation of avalanche frequency, magnitude, and costs. Existing inventories are incomplete, often restricted to fatal events, and rarely quantify socioeconomic impacts. Tourism disruptions, long-term forestry losses, and indirect transport costs remain largely undocumented.

Current records capture only direct impact (fatalities), short-term effects, generating high limitation in total impact estimates. Improved coordination, harmonized reporting, and integration of climate-related hazard interactions are essential for robust regional and European risk assessments.

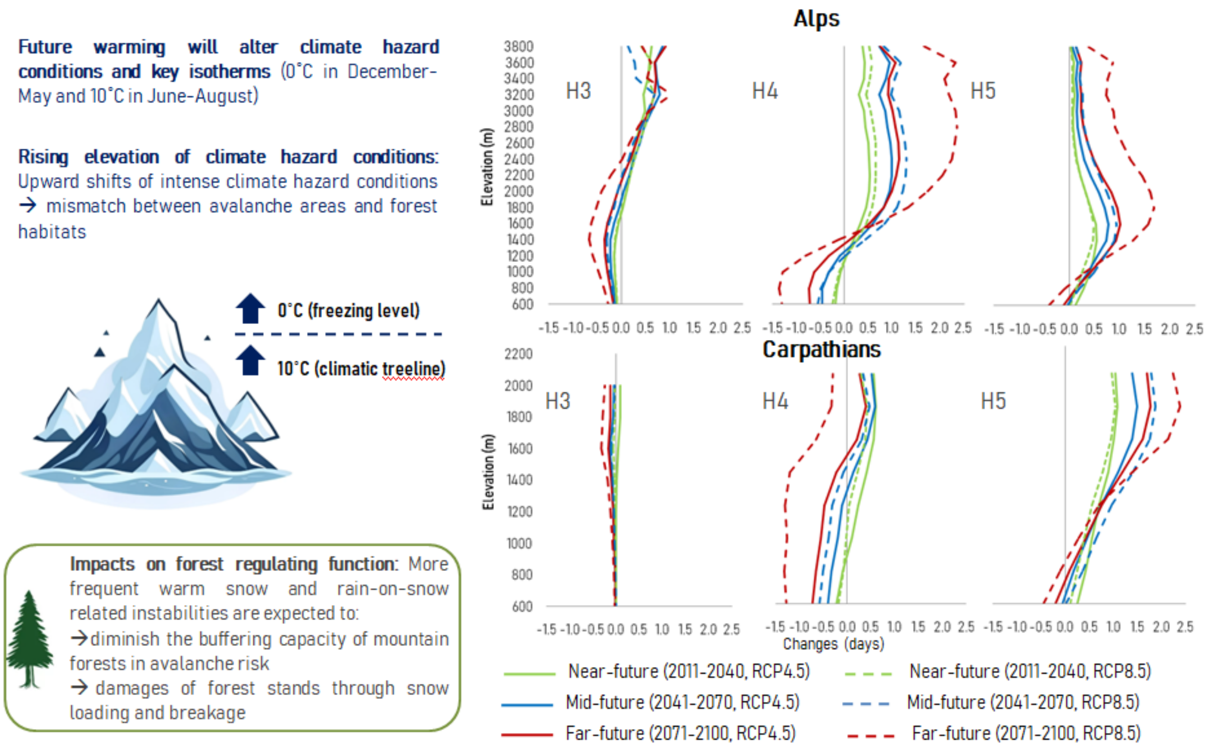
2.5.3. Ecosystem aspects in results

Ecosystem-related vulnerability in the Alpine and Carpathian regions centres on the capacity of mountain forests to reduce snow-avalanche likelihood and impacts, consistent with the CICES (v5.2) regulating services for buffering extreme events. In CS5, the CROSSEU assessment focuses on three key forest habitats identified in the Habitats Directive (Article 17) and EUNIS classifications: (i) Habitat 9410 – Acidophilous Picea abies forests (900-1,800 m), whose dense spruce stands stabilize snowpacks and enhance slope cohesion; (ii) Habitat 9420 – subalpine Larix decidua and Pinus cembra forests (1,500–2,200 m), which disrupt slab formation and dissipate avalanche energy; and (iii) Habitat 9430 – Pinus mugo scrub (1,600–2,200 m), whose multi-stemmed structure functions as a natural snow fence, limiting release zones and slowing small to medium avalanches. Figure CSA5_Figure 1 illustrates the spatial overlap between these habitats and documented avalanche fatalities (2017/18–2024/25). These forest types correspond largely to CLC 2018 classes 312 and 313.



CSA5_Figure1: Spatial distribution of coniferous forest habitats (according to Art. 17 – Habitat Directive) providing regulating ecosystem service against the snow avalanches in the European Alps and Carpathian Mountains.

In the Alps, the upward shift of the 0°C isotherm will shorten snow persistence and increase rain-on-snow (ROS) events at mid-elevations (1,200–1,800 m), weakening the stabilizing role of Picea abies-Abies alba protection forests (Habitat 9410) (CSA5_Figure2). Reduced snow anchoring and more frequent wet-snow instabilities will raise the likelihood of shallow avalanches on slopes that are currently stable. At the same time, the rise of the 10°C summer isotherm will drive Larix decidua and Pinus cembra (Habitat 9420) upslope. While this upward expansion may enhance protection near present-day treeline, regeneration delays on steep terrain and increased drought stress may limit stand density and cohesion, reducing long-term slope stability. Under RCP8.5, hazard indices show marked increases: H3 (warm-snow days) and H4 (warm-snow persistence) rise most strongly above 1,600-1,800 m, indicating more frequent and longer wet-snow conditions favourable to wet-slab avalanches. H5 (rain-on-snow events) increases at nearly all elevations, but especially between 1,200-2,000 m, overlapping with the main protection-forest zones. By the late century, ROS increases by 1-2 days per season, intensifying liquid-water loading on snow-covered slopes. Together, these changes mean that the most sensitive warm-snow regimes will increasingly coincide with the elevation range of the key Alpine protection forests (Habitats 9410 and 9420). More frequent and persistent warm-snow and ROS conditions are expected to reduce snowpack stabilisation, increase forest damage from wet-snow loads, and promote wet-slab and glide avalanches initiated within or just above the forest canopy. At higher elevations (>2,000 m), upslope movement of release areas will make Larix-Pinus cembra forests more important as buffering zones, although warming-driven reductions in stand density may weaken their long-term protective function.



CSA5_Figure2: Elevation-dependent changes in avalanche-relevant climate hazard indices (H3, H4, H5) and their implications for mountain forest regulation in the Alps and Carpathians

In the Carpathians, similar warming-driven shifts are projected, though with regionally varied intensity due to more continental climate conditions. The upward movement of the 0 °C isotherm will reduce the snow-retention capacity of Picea abies forests (Habitat 9410) in the 1,000-1,600 m belt, likely shifting the rain-snow transition zone upward by 200-400 m (CSA5_Figure 2). This is likely to expose lower elevations to more frequent wet-snow avalanches while potentially increasing forest stress from pests, and moisture deficits. Rising summer temperatures will also promote upslope migration of Pinus mugo (Habitat 9430), which may temporarily enhance slope roughness but could decline under sustained warming, weakening its role as a natural "snow fence". Overall, upward-shifting temperature thresholds will progressively displace the most effective avalanche-regulating forest belts to higher altitudes, creating periods of mismatch between forest protection zones and avalanche release areas, particularly in mid-elevation belts where infrastructure and tourism are concentrated. Maintaining forest protective functions will require adaptive management, including species diversification, assisted regeneration, and integration of climate projections into protection-forest planning. Future hazard indicators show moderate but elevation-sensitive increases in warm-snow instability. Changes are smaller than in the Alps but follow the same vertical pattern: H3 (warm-snow days) increases slightly at 1,400-1,800 m and declines below ~1,200 m as snow becomes scarce; H4 (warm-snow persistence) increases more clearly at >1,500 m under far-future RCP8.5; and H5 (rain-on-snow events) rises by up to 2-3 days at 1,000-1,600 m, directly affecting the core Habitat 9410 spruce belt. These changes are critical because Carpathian protection forests are already fragile due to shallow soils, pests, storm damage, and limited management. Increased warm-snow persistence and rain-on-snow events will heighten the likelihood of small wet avalanches, increase snow loading and forest damage, and reduce the continuity of Pinus mugo belts. Given the compressed elevation gradients in the Carpathians, even small upward shifts in warm-snow processes can rapidly eliminate the overlap between forest belts and avalanche starting zones, diminishing the effectiveness of natural forest protection.

2.5.4. Assessment of societal vulnerabilities

2.5.4.1. Qualitative findings from stakeholder engagement

Societal vulnerability to snow avalanches in the Alpine and Carpathian regions reflects the interplay between changing climatic conditions, socio-economic dependence on winter tourism, and varying institutional capacities for risk management. Although both mountain systems share similar topographic constraints and winter-focused economies, they differ markedly in governance maturity, data infrastructures, and adaptive capacity. Stakeholder engagement, through interviews and surveys with local authorities, emergency services, tourism operators, alpine guides, and avalanche control teams in Austria, Italy, and Romania, reveals distinct vulnerability patterns across the two regions. These insights complement the quantitative assessment in D2.2 and underscore how institutional readiness, public awareness, and climate-adaptation capacity collectively shape the evolving landscape of avalanche risk.

The Alps. Stakeholders from the Austrian Alps, including representatives from the Torrent and Avalanche Control Service (WLV), municipal authorities in Paznauntal/Galtür, and ski resort management entities, highlighted that despite a long tradition of risk management and institutional preparedness, the societal exposure to avalanches remains substantial and is likely to intensify under changing climate conditions. In terms of *institutional and technical capacities*, the alpine stakeholders reported high institutional awareness and a strong reliance on GIS-based hazard mapping, real-time sensor networks, and simulation models for avalanche forecasting and risk management. Daily monitoring and early warning systems are robust, and avalanche forecasting is embedded in the local governance frameworks (e.g., in Austria, Italy, Switzerland, France). The WLV's integrated daily monitoring and early warning systems into the local decision-making, supported by dense local observation networks and extensive drone-assisted terrain mapping. Nevertheless, even within these advanced systems, stakeholders expressed that rapid temperature changes and rain-on-snow events increasingly challenge predictive accuracy. The WLV highlighted that temperature variability has overtaken new snowfall as the dominant instability driver, while lower-elevation zones experience dryness and fire risk, signalling compounding climate stress. The same thought is shared also in the Italian Alps where, however, there is particular concern about the notable intensification (due to climate change) of other natural hazards - landslides, debris flows, etc.) in non-winter seasons.

Social and economic vulnerabilities. Tourism remains the cornerstone of local livelihoods in the alpine region. The case of the Galtür avalanche, remains a defining collective trauma and a pivotal learning event. New protective infrastructures (e.g., the "Alpinarium" memorial wall) symbolize a collective memory that shapes local community identity and safety culture. Yet, stakeholders acknowledged that the economic sustainability of winter tourism is under pressure, with diversification (e.g., mountain biking, summer tourism) becoming an adaptive strategy to maintain community income. With "44 days less snow than before," resort managers report growing dependence on artificial snow production, which raises energy costs and widens the gap between wealthy and less-resourced resorts. This trend drives spatial inequality in resilience, where affluent destinations adapt through technology, while smaller communities face economic precarity. Social and economic vulnerability is thus shifting from acute hazard exposure toward economic dependence on a diminishing snow season, coupled with rising adaptation costs and changing visitor behaviour.

Human perception and risk awareness. In the Alpine regions, social memory of past avalanche disasters reinforces the culture of risk and vigilance. The integration of commemoration practices and education (e.g., mountain guide schools, memorials, awareness programmes) has fostered strong local community awareness. However, stakeholders noted that tourists and recreational skiers often underestimate avalanche risks outside marked areas, posing persistent challenges for prevention and rescue services. Thus, while institutional vulnerability is low, human behavioural vulnerability, especially among recreational backcountry users, remains a critical issue. In the Italian Alps, stakeholders highlighted that preparedness levels have increased significantly in many municipalities, including among tourists, who now have broader access to information on avalanche-prone areas and recommended precautionary measures. However, this increased availability of information does not always translate into safer behaviour, as individuals do not consistently act on the guidance provided.

Interviewed stakeholders also highlighted climate change as both a hazard multiplier and economic disruptor. The retreat of the reliable snowlines (supporting the rentability of winter tourism), expansion of wet-snow avalanches, and growing costs of artificial snowmaking are reshaping

Alpine vulnerabilities from physical hazard exposure toward socioeconomic fragility and adaptation inequality.

The Carpathian Mountains. Stakeholders from the Carpathians (Romania) describe a markedly different vulnerability profile, shaped by fragmented institutions, limited data infrastructures, and low public awareness of avalanche risk.

Institutional vulnerabilities and data gaps. Interviews reveal the absence of a national avalanche inventory, standardized assessment protocols, and dedicated legislation. Data collection relies mainly on the Regional Weather Forecasting Service Sibiu, county Salvamont units, and volunteer platforms such as avalanseincarpati.ro. Stakeholders highlighted missing elements including insurance coverage, sustained funding for education, integration of climate projections, and cross-sector coordination among meteorology, forestry, and civil protection. As a result, avalanche hazards remain marginal in national policy, and early-warning tools such as Ro-Alert do not yet cover avalanches.

Socioeconomic vulnerabilities. Tourism-dependent regions (e.g., Sibiu, Maramureș, Nowotarski) face rising uncertainty due to variable snow conditions and limited adaptive capacity. Many Carpathian resorts lack artificial snowmaking, slope stabilization, or financial resources, leaving local economies exposed. Population decline reduces exposure but also weakens the workforce, funding, and institutional capacity needed for rescue operations and forest management. Protective forests are increasingly stressed by rain-on-snow events and degradation, further lowering natural resilience.

Human awareness and risk culture. Public and local authority awareness remains low, with avalanches perceived as rare compared to more familiar hazards. Awareness and training initiatives exist but remain sporadic and underfunded. Stakeholders also noted male dominance in rescue and technical services and limited community involvement in preparedness. Broader and more inclusive engagement, targeting tourists, residents and vulnerable groups, is urgently needed.

Overall, stakeholder insights underline that, unlike the Alps, where high exposure is offset by strong governance, the Carpathians experience moderate hazard but high vulnerability, driven by institutional, economic, and societal constraints (CSA5_Table 1).

CSA5_Table1: Comparative insights (Alps versus Carpathians) on societal and human vulnerability to snow avalanches

Aspects	European Alps	Carpathian Mountains
Institutional capacity	Advanced (formalized hazard mapping, monitoring, EWS)	Fragmented, limited to local initiatives

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Data and monitoring	Daily use of sensor networks and GIS	Sparse data, voluntary records, limited national framework
Economic exposure	High (dense tourism and infrastructure networks, often important for cross-border trade, as well as for local trade)	Moderate, but locally concentrated
Risk awareness	Strong institutional culture, high technical literacy; strong preparedness, including initiatives and tools for increasing tourists' awareness,	Low awareness, limited training
Climate adaptation	Active implementation (e.g., barriers, snowmaking	Passive adaptation, reactive measures

2.5.4.2. Capabilities impacted

CS5 integrates key regional and sectoral vulnerabilities related to four of Nussbaum's capability categories related to the transport, tourism, forestry, and mountain communities (CSA5_Table2).

CSA5_Table 2: CS5 capability categories and selected indicators

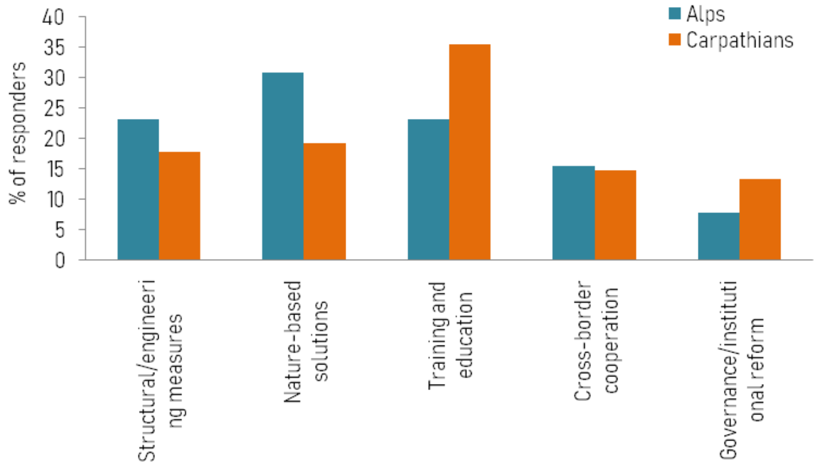
Capability (Nussbaum's categories)	Functioning	Wellbeing relevance	Influenceability	Indicators (qualitative/quantitative) for measuring the capability
Being able to be mobile (Bodily integrity)	Mobility, safety, accessibility	Basic needs, safety and security	Medium	Road density intersecting moderate to very high avalanche susceptibility zones
Being sheltered (Bodily health, life)	Access to safe tourist housing and infrastructure	Basic needs, safety	Medium-to-high	Number of alpine huts located in moderate to very high avalanche susceptibility zones
Being able to enjoy recreational activities (Play)	Safety and security in recreational activities	Basic needs, safety	Low-to-medium	Number of ski slopes intersecting moderate to very high avalanche susceptibility zones
Being able to live in flourishing environment (Environment)	Ecosystem stability, protective services	Environment well-being	Low-to-medium	% of Natura2000 sites located in moderate to very high susceptibility zones % of natural parks in in moderate to very high susceptibility zones

2.5.5. Synthesis and Priorities for Action

Stakeholder consultations conducted in October-November 2025 with 46 sectoral stakeholders across the Alps and the Carpathians highlight that snow avalanche risk under climate change is increasingly shaped by institutional, socioeconomic, and governance factors, rather than by physical hazard dynamics alone. Accordingly, priorities for action converge around four interlinked domains.

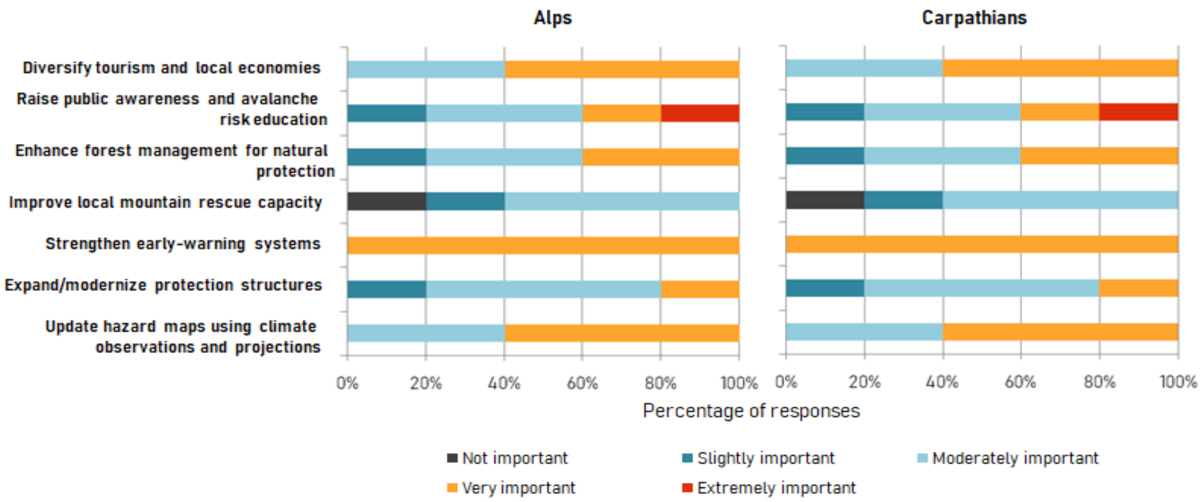
- Strengthening climate-informed governance and institutional coordination emerges as a central priority, particularly in the Carpathians. Stakeholders consistently emphasize the need to improve coordination between meteorological services, civil protection, forestry, and land-use planning authorities. Integrating climate projections into national avalanche hazard mapping and long-term planning frameworks implies moving beyond historically based assumptions and ensuring that hazard maps and risk-management instruments are periodically reviewed to reflect the emerging non-stationary snow and climate conditions (e.g., including the increasing relevance of wet-snow and rain-on-snow processes).
- Improving data availability, harmonisation, and cross-regional cooperation is identified as a prerequisite for effective risk management. While Alpine regions benefit from advanced monitoring networks and standardized practices, Carpathian countries face fragmented data systems, incomplete inventories, and limited use of GIS-based tools. Stakeholders underline the importance of shared methodologies, interoperable datasets, and cross-border collaboration to support early-warning systems, impact assessments, and evidence-based decision-making. Priority actions also include improving the consistency of avalanche inventories, enhancing the use of climate and snowpack data in operational workflows, and reinforcing cross-border cooperation to enable comparable assessments and shared learning between regions.
- Enhancing public awareness, targeted risk training and education, and risk culture is highlighted as a cost-effective and urgently needed measure, especially in regions with expanding tourism and limited technical capacity (especially in the Carpathians). Participants stress the importance of targeted education for tourists, youth, and local communities, alongside sustained investment in professional training for rescue services, forest managers, and local authorities. Furthermore, improving the translation of scientific knowledge into practice remains a priority. Climate-aware risk communication should support both professionals and the public in understanding changing avalanche conditions and managing increasing uncertainty, thereby reinforcing preparedness and adaptive capacity.
- Investment priorities reflect regional differences in adaptive capacity and long-term resilience goals and should be tailored to regional contexts. In

the Alps, stakeholders support a balanced strategy focused on upgrading existing systems through nature-based solutions, updated hazard maps, and structural/engineering measures especially in high-exposure corridors. In contrast, Carpathian stakeholders prioritize foundational capacity building, including awareness raising, training and education, governance reform, and ecosystem-based protection, before advancing toward more technically demanding interventions (CSA5_Figure 3).



CSA5_Figure 3: Which type of investment offers the greatest long-term resilience to avalanche risk?

Overall, stakeholder perspectives on key avalanche-risk adaptation actions differ markedly between the two mountain regions. The rank of adaptation actions in snow avalanche risk management is shown in CSA5_Figure 4.



CSA5_Figure 4. What is the rank of adaptation actions in snow avalanche risk management?

Key barriers to avalanche-risk adaptation differ markedly between the Alps and the Carpathians. In the Alps, adaptation is constrained primarily by institutional and socio-economic factors rather than technical capacity, including tensions between tourism and safety, low political urgency due to the rarity of major events, underuse of climate projections despite strong

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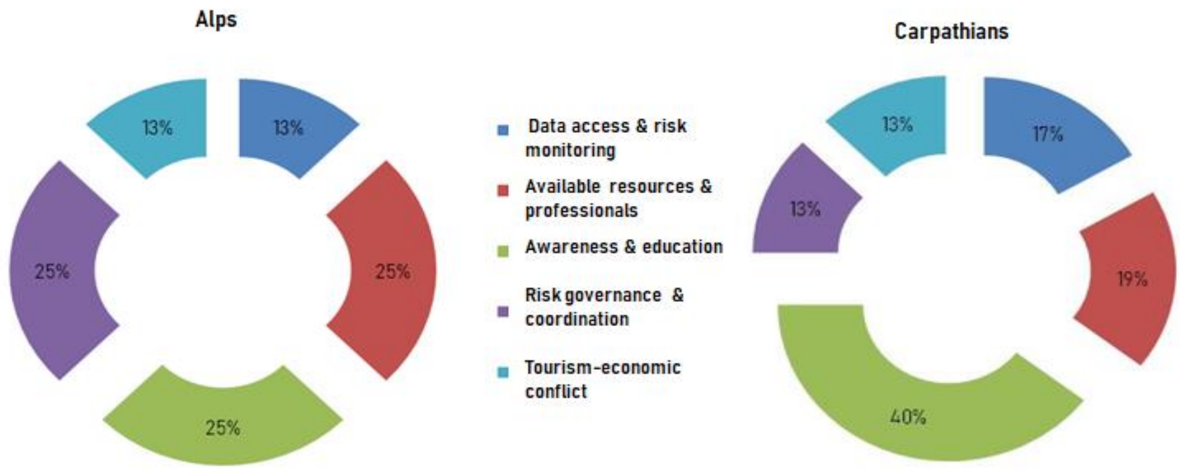
monitoring systems, fragmented governance, and a shortage of young avalanche professionals. These barriers indicate a mature system requiring improved coordination and climate-informed updates rather than fundamental capacity building. In contrast, the Carpathians face more structural challenges, such as insufficient monitoring and data availability, emerging early-warning capabilities, chronic underfunding and skills shortages, low public awareness, and fragmented institutional responsibilities. Addressing these foundational gaps is a prerequisite for implementing advanced climate-adaptation measures. Figure CSA5_Figure 5 summarises the perceived barriers in both regions.



CSA5_Figure5: The main barriers limiting effective avalanche-risk adaptation in the Alpine and Carpathian countries.

Case Study 5 shows that snow-related hazards, particularly avalanches, create societal and human vulnerabilities in the European Alps and Carpathians that extend beyond direct physical damage and fatalities. Strong regional contrasts emerge, with Alpine areas characterised by more mature preparedness and early-warning systems, while Carpathian regions remain more reactive and institutionally constrained. Impacts on key capabilities such as safe mobility, tourism- and forestry-based livelihoods, and psychological well-being are often indirect, underreported and unevenly distributed. Increasingly important compound processes, such as rain-on-snow events, further intensify risk, underscoring the need to integrate social, institutional and ecosystem-based dimensions into avalanche risk assessments.

Further work in Case Study 5 will focus on the development and implementation of standardised Integrated Risk Indicators (IRIs) into the CROSSEU DSS to estimate the change in the potential (current and future) socio-economic risks from snow avalanches in the European Alps and Carpathians under different climate scenarios. The IRI framework will enable the upscaling of avalanche risk assessments beyond documented storylines and hotspots, supporting an informed climate adaptation in key sectors such as tourism, transport and forestry, as well as for mountain communities.

2.6. #6 INDIRECT (Cross-sectoral multi-hazard risk)

2.6.1. Summary of Key Risks from D2.2

The Lower Danube River floodplain stands at the frontline of climate change impacts in Southeast Europe. The storyline events – catastrophic floods like that of 2006 and unprecedented droughts like 2022 – are signals of a new normal where extremes are more frequent. Historic discharge data and future projections (RCP4.5 and RCP8.5 scenarios) jointly indicated a trend toward greater hydrological volatility: more frequent & intense floods on one hand, and longer & harsher droughts on the other. The analysis identified that the highest risks concentrate in the Danube floodplain corridor, where both flood hazard and social vulnerability peak. Poor, rural communities behind aging dikes face the burden of floods, and the same communities suffer most in droughts due to their reliance on rain-fed agriculture. Without intervention, climate change could widen this vulnerability gap, hitting hardest those least able to cope.

2.6.2. Ecosystem aspects in results

Drought–flood alternation is a powerful ecological stressor with great consequences for ecosystems and biodiversity (IPCC, 2021). Unlike isolated droughts or floods, the rapid oscillation between extremes exerts compound stresses on ecological systems. Ecosystems in the Lower Danube Wetland System are adapted to a relatively predictable pattern of wet and dry cycles and now face abrupt variability that disrupts physiological processes, species interactions, and habitat stability. Organisms are adapted to particular hydrological regimes and sudden alternation between water scarcity and excess often pushes them beyond their physiological limits. Repeated cycles may shorten growth periods, delay flowering and fruiting, and lower reproductive success. Species tolerant of both extremes, including many invasive species, gain an advantage. Native species often have narrower tolerance ranges and cannot match the rapid shifts, leading to competitive exclusion.

Alternating drought and flood conditions disrupt biogeochemical cycles. During drought, reduced soil moisture limits microbial activity, slowing decomposition and nutrient mineralization. Nutrients accumulate in organic forms or are locked in dry soils. When flooding suddenly occurs, the pulse of water mobilizes accumulated nutrients, causing nutrients to flush into the waterways. This can lead to algal blooms in rivers and lakes, oxygen depletion from decomposition of organic matter, fish kills triggered by sudden drops in dissolved oxygen. The nutrient imbalance also affects terrestrial ecosystems. Soils lose fertility when nutrients are washed away, impairing plant regrowth in post-flood conditions.

Riverine and freshwater ecosystems are particularly vulnerable because hydrological stability is critical to their functioning. Drought reduces flow, increases water temperature, and concentrates the pollutants. Flooding that follows brings sediment surges, destroys spawning grounds, and can disrupt the life cycles of fish species. Fish and molluscs species rely on specific water levels and flow patterns. Rapid alternation between extremes can eliminate breeding windows, reduce juvenile survival, and fragment populations. Aquatic invertebrates, which form the base of food webs, are often most severely affected, leading to cascading effects on higher trophic levels.

Ecosystems with high biodiversity typically exhibit greater resilience. However, repeated extremes undermine this buffer by eroding structural complexity and functional redundancy. As resilience declines, ecosystems become more vulnerable to future disturbances, and their ability to provide essential ecosystem services (e.g., water purification, carbon storage, pollination, and climate regulation) diminishes.

Ecosystem services are the contributions of ecosystems – through their structures, processes, and functions – to human well-being (Constanza, et al., 1997). The Millennium Ecosystem Assessment (MEA, 2005) popularized the term and emphasized the link to human well-being across scales. CICES (Common International Classification of Ecosystem Services) (Haines-Young & Potschin-Young, 2018) reframes services as final ecological contributions to people, distinguishing them from intermediate processes and aligning with accounting needs.

Evaluating ecosystem services requires a combination of biophysical, socio-cultural, and economic methods that capture both the ecological functioning of landscapes and the values attributed to them by society. Biophysical assessments quantify ecological processes – such as water retention, carbon sequestration, or habitat quality – using ecological indicators, hydrological and biodiversity data, spatial modelling, and field measurements. Economic evaluation complements these analyses by estimating the monetary value of ecosystem services through approaches such as market pricing, avoided damage costs, replacement costs, production functions, or stated-preference methods. Socio-cultural evaluation adds a critical human dimension by documenting how communities perceive, use, and value ecosystems through interviews, participatory mapping, and surveys. Together, these methods allow a comprehensive assessment of ecosystem services that reflects not only ecological performance but also societal needs and trade-offs across alternative management scenarios.

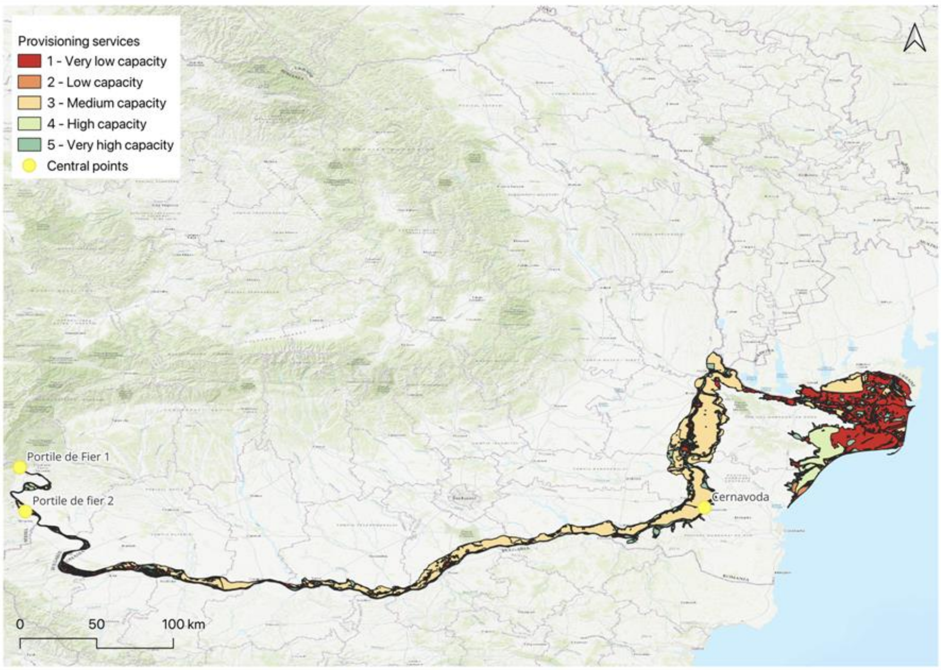
Along the Lower Danube Wetland System in Romania, hydrological alteration, land reclamation, and intensification of agriculture have profoundly modified floodplain structure and functioning, leading to a decline in ecological integrity and a reduced capacity to deliver key ecosystem services. At the same time, the region remains of strategic importance for biodiversity conservation, climate adaptation, and sustainable development, particularly in the context of the EU Biodiversity Strategy, the Nature Restoration Law, and integrated river basin management.

In this context, there is a growing need for spatially explicit, transparent, and decision-oriented methods that can capture the multifunctionality of floodplain landscapes and support the evaluation of alternative land-use and restoration pathways. Ecosystem services assessments provide a powerful framework for linking ecological processes to societal benefits, enabling the identification of trade-offs and synergies among provisioning, regulating, and cultural services, while explicitly acknowledging the role of biodiversity as the foundation of ecosystem functioning.

Our methodology is built on a spatially explicit assessment of ecosystem service (ES) potential for the Lower Danube Wetland System in Romania, integrating ecological indicators, hydrological processes, biodiversity attributes, and socio-economic context within a unified conceptual framework. We applied the ecosystem services matrix (Campagne et al. 2020) as the core methodological tool to systematically link ecosystem types with their capacity to supply provisioning, regulating, and cultural ecosystem services, as well as biodiversity support. Expert knowledge of the floodplain landscape — drawing on long-term ecological understanding, field experience, and regional studies — was used to assign relative ES supply scores to each ecosystem type, reflecting their potential capacity rather than actual use or demand. Ecosystem services were mapped by intersecting land cover and habitat data with matrix-based ES potential values, generating spatially explicit indicators of service provision across the floodplain. Regulating services included flood retention, water purification, climate regulation, and erosion control, which are strongly influenced by hydrological connectivity and wetland extent. Provisioning services encompassed food production, fisheries, biomass, and freshwater resources, while cultural services captured recreation, aesthetic value, education, and cultural heritage associated with the Danube floodplain landscape. Biodiversity was treated both as a supporting function and as an explicit conservation value, reflecting habitat quality, species richness potential, and ecological integrity.

This spatially explicit approach allows us to compare the capacity of the landscape to deliver ecosystem services under business-as-usual, partial restoration, and full nature-based restoration, providing a robust decision-support tool for policymakers, conservation practitioners, and local communities.

The spatial distribution of provisioning ecosystem services (ES) potential (CSA6_Figure 1) along the Lower Danube Wetland System in Romania, is expressed as relative capacity classes ranging from very low to very high. Overall, provisioning services are unevenly distributed along the river corridor, reflecting variations in floodplain width, land-use intensity, hydrological connectivity, and ecosystem type.



CSA6_Figure 1 - Lower Danube River floodplain ecosystem services: provisioning services capacity

Large stretches of the Lower Danube floodplain exhibit low to medium provisioning service potential, particularly in sections dominated by regulated riverbanks, embankments, and intensively managed agricultural land. In these areas, floodplain disconnection and landscape simplification constrain the capacity of ecosystems to support diverse provisioning services beyond crop production, resulting in more uniform and moderate ES potential values.

In contrast, areas with high to very high provisioning service potential are concentrated in wider floodplain sections and complex wetland systems, most notably in the downstream reaches and the Danube Delta. These zones are characterized by mosaics of wetlands, riparian forests, lakes, and channels that support a broad range of provisioning services, including fisheries, biomass production, reed harvesting, freshwater resources, and traditional food provisioning. The spatial clustering of high-capacity classes highlights the strong dependence of provisioning services on hydrological connectivity and habitat diversity.

Upstream sections of the Lower Danube show more fragmented patterns, with isolated patches of higher provisioning potential embedded within predominantly lower-capacity landscapes. These patches often correspond to remnant floodplain areas, side channels, or less intensively managed zones where natural processes are partially preserved. Their presence underscores the importance of remaining semi-natural floodplain elements for sustaining provisioning services, even within highly modified river segments.

Overall, the map indicates that provisioning ecosystem services potential increases downstream, following a gradient of increasing floodplain complexity and wetland extent. The results emphasize that while provisioning services are often associated with agricultural production, their long-term sustainability and diversity are closely linked to intact floodplain ecosystems. This spatial pattern supports the argument that nature-based restoration measures enhancing floodplain connectivity and habitat heterogeneity can strengthen provisioning services, particularly when integrated with multifunctional land-use strategies rather than single-purpose production systems.

CSA6_Figure 2 depicts the spatial distribution of regulating ecosystem services (ES) potential along the Lower Danube floodplain system in Romania, expressed as relative capacity classes from very low to very high. Regulating services—such as flood attenuation, water purification, climate regulation, sediment retention, and erosion control—show a pronounced spatial gradient closely linked to floodplain width, hydrological connectivity, and the presence of semi-natural ecosystems.

Sections of the Lower Danube characterized by narrow, embanked, or highly regulated floodplains predominantly exhibit low to very low regulating service potential. In these reaches, the disconnection between the river and its floodplain limits the capacity of ecosystems to store floodwaters, retain sediments and nutrients, and regulate microclimatic conditions. These patterns are particularly evident in upstream and midstream segments where river engineering and intensive land use have constrained natural floodplain processes.

In contrast, areas with high and very high regulating service potential are concentrated in downstream sections of the river, especially in wider floodplain zones and the Danube Delta. These areas support extensive wetlands, riparian forests, lakes, and secondary channels that enhance

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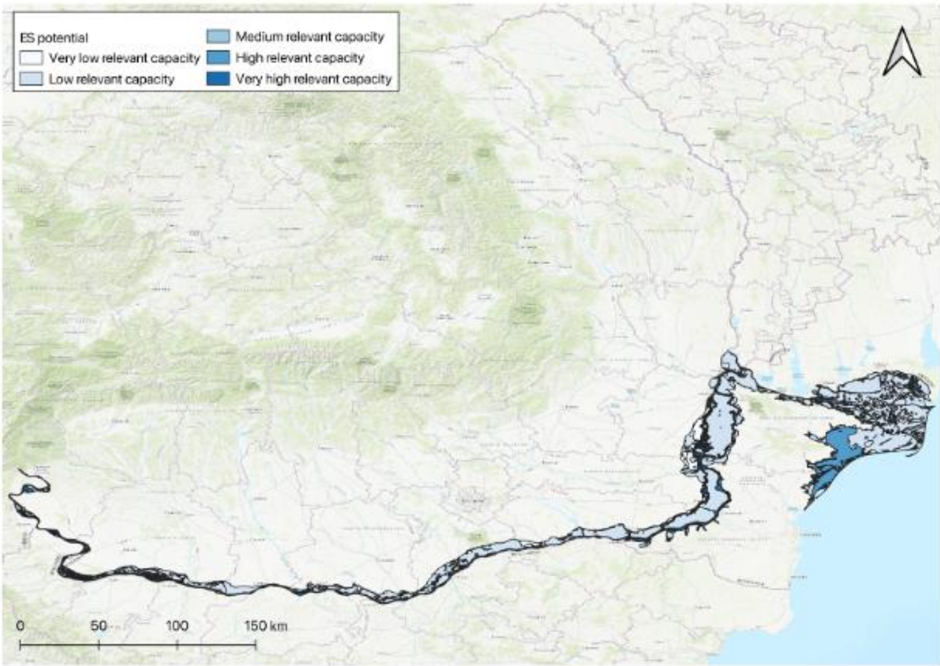
water retention, nutrient cycling, and carbon sequestration. The spatial continuity of high-capacity classes in these regions highlights the critical role of intact floodplain ecosystems in regulating hydrological and biogeochemical processes at the river basin scale.

Intermediate classes of regulating service potential occur in partially connected floodplain segments, where remnant wetlands, side arms, and less intensively managed land still provide meaningful regulatory functions. These areas form transitional zones that retain a degree of natural functionality and represent strategic opportunities for restoration measures aimed at enhancing floodplain connectivity and ecosystem performance.

Overall, the map reveals that regulating ecosystem services are highly sensitive to floodplain degradation and restoration, more so than provisioning services. The strong downstream increase in regulating capacity underscores the cumulative benefits of landscape complexity and hydrological connectivity. These results emphasize that nature-based restoration of floodplains—through reconnection of wetlands and reactivation of natural flooding regimes—can substantially enhance regulating services, contributing to flood risk reduction, water quality improvement, and climate resilience for both local communities and downstream ecosystems.



CSA6_Figure 2 - Lower Danube River floodplain ecosystem services: regulating services capacity

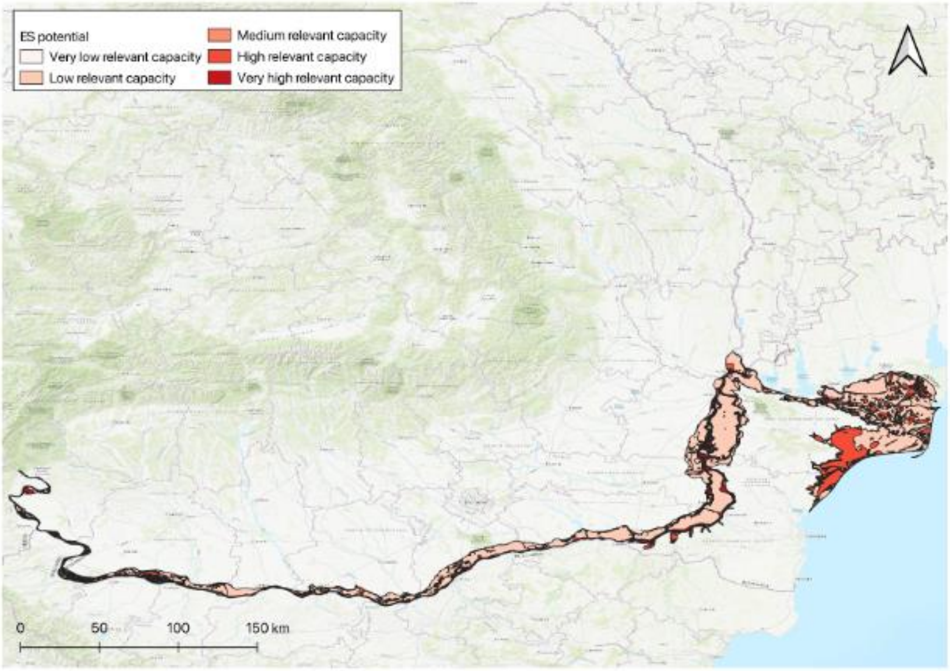
The spatial distribution of cultural ecosystem services (ES) potential (CSA6_Figure 3) along the Lower Danube floodplain system in Romania, expressed as relative capacity classes from very low to very high. Cultural services—including recreation, tourism, aesthetic appreciation, education, and cultural heritage—display a heterogeneous spatial pattern that reflects the interplay between landscape naturalness, accessibility, scenic value, and the presence of iconic floodplain ecosystems.

Across much of the Lower Danube corridor, low to medium cultural service potential dominates, particularly in sections characterized by simplified river landscapes, embanked floodplains, and intensive agricultural use. In these areas, the visual and experiential qualities of the landscape are reduced, limiting opportunities for nature-based recreation and cultural engagement despite the proximity of the river.

In contrast, high and very high cultural ecosystem service potential is concentrated in downstream reaches, most notably within the Danube Delta and adjacent floodplain areas. These zones combine high landscape diversity, extensive wetlands, open water bodies, and rich biodiversity, which together underpin strong aesthetic values and recreational opportunities. The prominence of very high-capacity classes in the delta reflects its international recognition for nature-based tourism, environmental education, and cultural identity, as well as its symbolic role in regional and national heritage.

Upstream and midstream sections of the floodplain exhibit localized hotspots of elevated cultural service potential, often associated with remaining natural river stretches, oxbow lakes, riparian forests, or protected areas. These isolated patches highlight the importance of semi-natural landscapes for providing cultural benefits even within heavily modified river systems. Their fragmented distribution, however, indicates limited spatial continuity of cultural services outside the delta region.

Overall, the map reveals a clear downstream gradient of increasing cultural ecosystem service potential, closely aligned with improvements in ecological integrity and landscape heterogeneity. The results underscore that cultural services are strongly dependent on the preservation of natural floodplain features and biodiversity, rather than on intensive land use. Consequently, nature-based restoration measures that enhance landscape diversity, water–land interactions, and ecological connectivity are likely to generate substantial co-benefits for recreation, tourism, and cultural well-being, reinforcing the social value of floodplain restoration in the Lower Danube system.



CSA6_Figure 3 - Lower Danube River floodplain ecosystem services: cultural services capacity

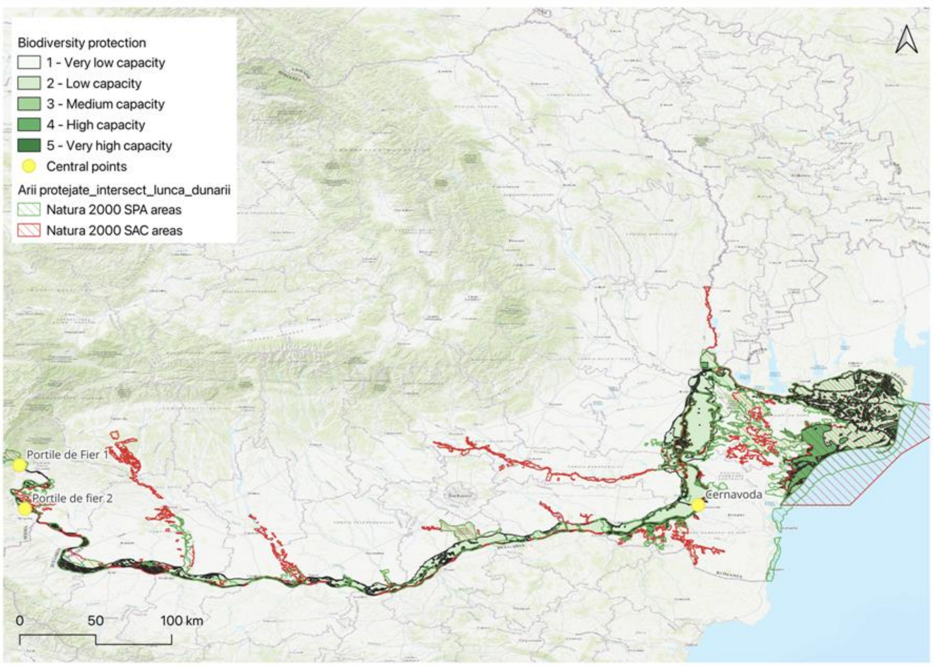
The spatial distribution of biodiversity protection potential (CSA6_Figure 4) along the Lower Danube Wetland System in Romania, is classified into five capacity levels ranging from very low to very high. This assessment reflects the relative capacity of floodplain ecosystems to support habitats, species diversity, and ecological integrity, and is interpreted in relation to the existing Natura 2000 network, including Special Protection Areas (SPAs) and Sites of Community Importance (SCIs / SACs).

Areas exhibiting high to very high biodiversity protection potential are predominantly concentrated in the downstream sections of the Lower Danube, particularly in the Danube Delta and adjacent floodplain complexes. These zones coincide extensively with Natura 2000 SPAs and SACs, underscoring a strong spatial alignment between areas of high ecological value and existing conservation designations. The overlap highlights the critical role of wetlands, riparian forests, lakes, and secondary channels in sustaining species-rich habitats, migratory bird populations, and aquatic biodiversity of European importance.

Along the middle reaches of the Lower Danube, high-capacity biodiversity areas occur in a more fragmented pattern, often corresponding to remnant floodplain sections, protected islands, and riparian corridors. Many of these patches overlap with designated Natura 2000 sites, indicating that conservation efforts have prioritized ecologically valuable areas. However, the spatial discontinuity of these high-capacity zones also reflects historical floodplain alteration and hydrological disconnection, which have reduced habitat continuity and limited species dispersal.

Sections characterized by low to very low biodiversity protection potential are mainly associated with heavily modified river stretches, embanked floodplains, and intensively managed agricultural areas. In these reaches, limited overlap with Natura 2000 sites is observed, reflecting reduced habitat quality, simplified ecosystem structure, and diminished ecological functionality. Nevertheless, some Natura 2000-designated areas extend into zones of medium biodiversity potential, suggesting opportunities where improved management or restoration could enhance conservation outcomes within the existing protected-area framework.

Overall, the map demonstrates a strong correspondence between high biodiversity protection potential and Natura 2000 SPAs and SACs, validating the ecological relevance of the network along the Lower Danube floodplain. At the same time, the presence of medium-capacity areas adjacent to protected sites highlights key opportunities for ecological connectivity enhancement and buffer zone restoration. Strengthening hydrological and habitat connectivity between Natura 2000 sites could significantly improve the coherence of the network, supporting species movement, climate adaptation, and long-term biodiversity resilience across the Lower Danube system.



CSA6_Figure 4 - Lower Danube River floodplain ecosystem services: biodiversity protection capacity

Changes in ecosystem extent, structure, and connectivity under each scenario were translated into shifts in ES potential, allowing us to quantify trade-offs and synergies among service categories. This approach highlights how restoration of floodplain wetlands and natural hydrological regimes can enhance regulating and cultural services while supporting biodiversity, often with limited losses—or even gains—in provisioning services.

2.6.3. Gender and social inclusion Dimensions

Drought–flood alternation in the Lower Danube floodplain compounds existing social vulnerabilities and produces gender-differentiated impacts. Women, elderly people, ethnic minorities, and low-income households are disproportionately affected because of pre-existing inequalities in assets, access to services, decision-making, and formal safety nets. These inequities shape exposure, sensitivity, and adaptive capacity in ways that make recovery and long-term resilience unequal across social groups.

Many households in the Lower Danube depend on agriculture, small-scale fisheries, and seasonal labour - where women often hold insecure, informal roles or are secondary earners. Droughts reduce harvests and fish yields; sudden floods then destroy stored seed, equipment, or homes, producing repeated asset losses that female-headed or low-asset households are least able to absorb.

In flood or drought emergencies, care responsibilities (water collection, child and elder care, food preparation) typically increase for women, constraining their time for paid work. Reduced access to water and health services during extremes heightens risks for maternal and child health and for people with chronic conditions.

Women and marginalized groups frequently have less access to early-warning information, land tenure, credit, and formal decision-making spaces for flood/drought planning.

Addressing drought–flood alternation in the Lower Danube River floodplain requires interventions that go beyond infrastructure: social policies must explicitly correct gender and inclusion gaps.

2.6.4. Assessment of Societal and Human Vulnerabilities

Qualitative Findings from Stakeholder Engagement

In CS#6, stakeholders (Danube Delta Research and Development Institute, Institute for Hydrology and Water Management, National Institute for Research and Development in Forestry "Marin Dracea", University of Bucharest, Braila Agricultural Research and Development Station,

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Romanian Meteorological Administration, Danube Delta Biosphere Reserve Administration, Small Island of Braila Natural Park Administration, WWF Romania, Ministry of Environment) were involved during a workshop, held on November 28th, 2024, in which they were asked to identify the events/hazards associated with climate change in the Lower Danube River floodplain.

Stakeholders identified the following events/hazards associated with climate change in the Lower Danube River floodplain: droughts, pedological drought, soil water deficit, extreme and persistent heat, scorching heat, lack of water in wetlands, changes in the distribution of precipitations, drying of vegetation, extreme temperatures, shortening of the vegetation period with an impact on agricultural production and its quality, lowering of the water table, early rise in spring temperatures, increasing the amount of temperature degrees useful for spring crops, predictability of climatic conditions for the adaptation of agricultural technologies, lack of snow, floods, phase shift of flood waves, decrease in the number of flood days in natural flooding areas.

Capabilities Impacted

CSA6 integrates key regional and sectoral vulnerabilities related to four of Nussbaum's capability categories related to the biodiversity, agriculture, tourism, and communities (CSA6_Table 1).

CSA6_Table 1 - Capability categories in Lower Danube floodplain

Capability (Nussbaum's categories)	Functioning	Wellbeing relevance	Influenceability	Indicators (qualitative/quantitative) for measuring the capability
Being able to live in flourishing environment (Environment)	Well-functioning ecosystems able to supply ecosystems services	Environment well-being	Medium	% of Natura2000 sites located in moderate to very high susceptibility zones % of natural parks in in moderate to very high susceptibility zones Number of tourists visiting protected areas in the Lower Danube region
Being sheltered (Bodily health, life)	Safety and security	Basic needs, safety	Medium-to-high	Number of homes damaged

Being able to hold property (Control over one's environment (Material))	Maintain stable income and living standards under climate stress.	Living conditions	Medium	Surface of flooded/drought affected agricultural land
Being able to be nourished (Bodily Health)	Access to sufficient food and income to maintain nutrition and health.	Basic needs	Medium	Crops affected by drought/flood

2.6.5. Synthesis and Priorities for Action

Along the Lower Danube Wetland System in Romania, decades of river regulation, land reclamation, and agricultural intensification have significantly altered floodplain structure and reduced the capacity of ecosystems to deliver key provisioning, regulating, cultural, and biodiversity-related services. At the same time, the region remains strategically important for biodiversity conservation, climate adaptation, and sustainable development, especially within the context of EU environmental and water policies. There is therefore a clear need for spatially explicit and decision-oriented methods that can support the evaluation of alternative floodplain management and restoration pathways.

By operationalizing expert knowledge through the ecosystem services matrix and embedding it within a GIS-based framework, our methodology provides a robust, reproducible, and policy-relevant decision-support tool. It supports evidence-based planning by making ecosystem service capacities visible, comparable, and spatially explicit, thereby informing policymakers, conservation practitioners, and local communities about the implications of alternative floodplain management pathways for sustainable development, climate adaptation, and biodiversity conservation in the Lower Danube region.

2.7. #7 INDIRECT (Power System)

2.7.1. Summary of Key Risks from D2.2

The European electricity system is increasingly exposed to compound climate hazards (CCHs)-heatwaves, drought, and extended periods of low renewable generation that can simultaneously affect electricity demand, supply, and transmission flows (IPCC, 2021). Case Study 7 (CS7) addresses these indirect impacts on the power system. The objective is to provide a fully quantitative assessment of how climate-driven variability influences electricity system adequacy, operational costs indicators, and cross-border resilience.

France and its neighbouring interconnected regions were selected as the primary focus due to their high reliance on nuclear and renewable power (IEA, 2025), sensitivity to temperature-dependent demand, and their central role in European power exchanges (De Felice et al., 2023). The earlier conceptual insights from D2.2 are here followed up by a robust ensemble-based assessment built on climate-forced energy indicators and energy system simulations.

2.7.2. Supplementary issues related to D2.2

Data, Models and Analytical Framework

The assessment integrates climate-forced energy indicators with the plan4res power system model to quantify how concurrent and more extreme climate hazards influence electricity system performance across France and interconnected European regions. The modelling workflow couples high-resolution climate input data with hourly demand and renewable generation potentials, ensuring that the full range of plausible meteorological conditions expected for 2030 is captured. In the following months, also 2050 will be run and assessed, together with a historical run using ERA5 derived energy indicators creating a baseline to assess the future scenarios against.

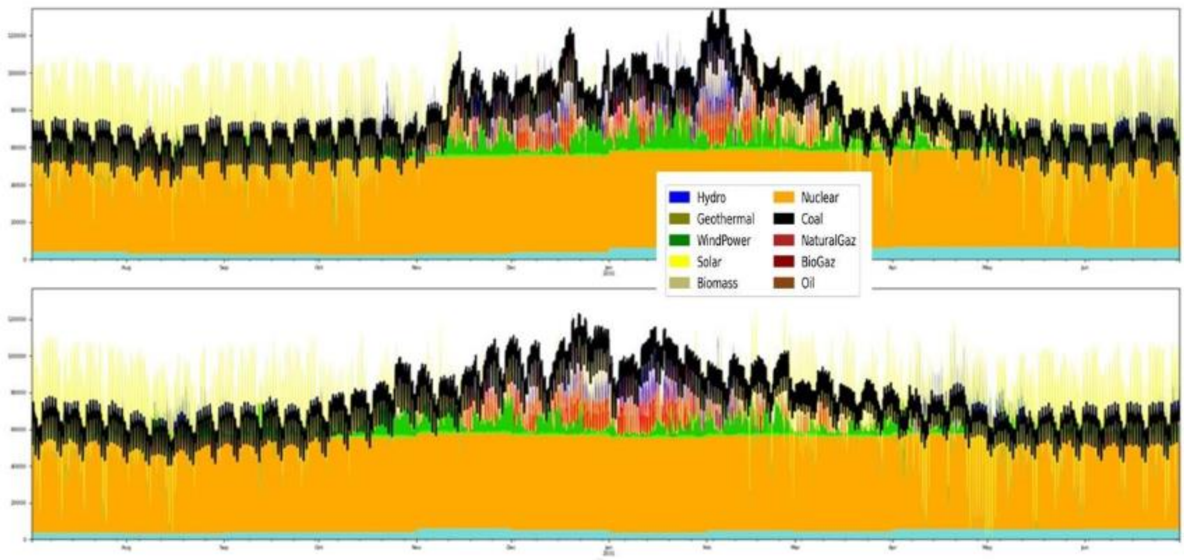
Five CMIP6 climate projections are used (see details in D2.2), each providing 21 ensemble years representing 105 distinct but equally plausible climate years. The ensemble years are constructed by using the closest +-10 years of hourly data, given a better estimate of year-to-year variability in climate and weather events than running a single year. From these, hourly wind potential, solar PV potential, temperature-sensitive demand time series, and monthly hydropower inflow estimates were generated. These climate indicators act as direct inputs to the plan4res simulations. As of the current status of the case study, we ran the model first in a test mode. The results here are from 21 ensemble years instead of the full 105 year ensemble system for the SSP370 climate scenario, which is being run at the time of writing this deliverable. Additional climate scenarios will be evaluated as well, see details in D2.2. The model chosen was the MPI-ESM1-2-HR which is a high-resolution CMIP6 Earth system model developed by the Max Planck Institute for Meteorology.

The plan4res model then simulates the power system at hourly resolution, enforcing generation constraints, interconnector limits, reservoir dynamics, and economic dispatch of resources (plan4res Consortium, 2025; Beulertz et al., 2019; Beulertz et al., 2020; Most et al., 2020). For each ensemble year, the model produces hourly values for electricity generation by technology, demand, marginal costs, imports, exports, and instances of unmet demand. Analytically, the study follows six key steps: (1) aggregation of hourly demand, generation, and costs across all ensemble years; (2) calculation of hourly net energy balance; (3) detection and quantification of periods of unmet demand; (4) event-based characterization of deficit events (duration and magnitude); (5) analysis of marginal cost variability; and (6) integration of societal vulnerability indicators.

Unmet demand events were identified whenever electricity demand exceeded available generation. These hours were then clustered into discrete events, allowing calculation of event duration, severity, and recurrence across ensemble years.

Climate-Driven System Impacts: Hazards and Performance Outcomes

Across the 21 climate ensemble years, strong meteorological variability produces pronounced shifts in renewable generation, cooling-water availability, demand profiles, and cross-border exchange patterns. These climate-forced variations generate distinct patterns of operational stress, including hours of unmet demand, periods of elevated marginal costs, and system-wide adequacy challenges (IEA, 2024).



CSA7 Figure 1: Two years of modled hourly energy mix for France, the different colors highlight different types of electricity generation. The timeseries runs from July to July the following year.

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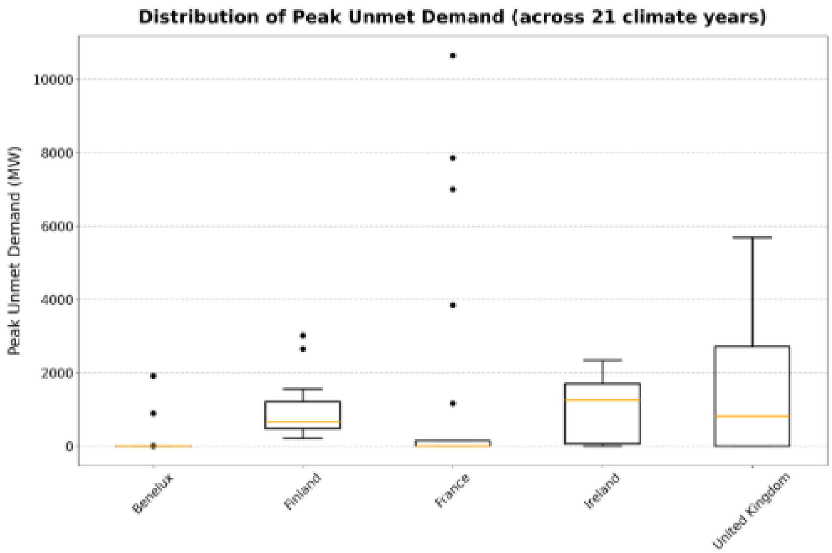
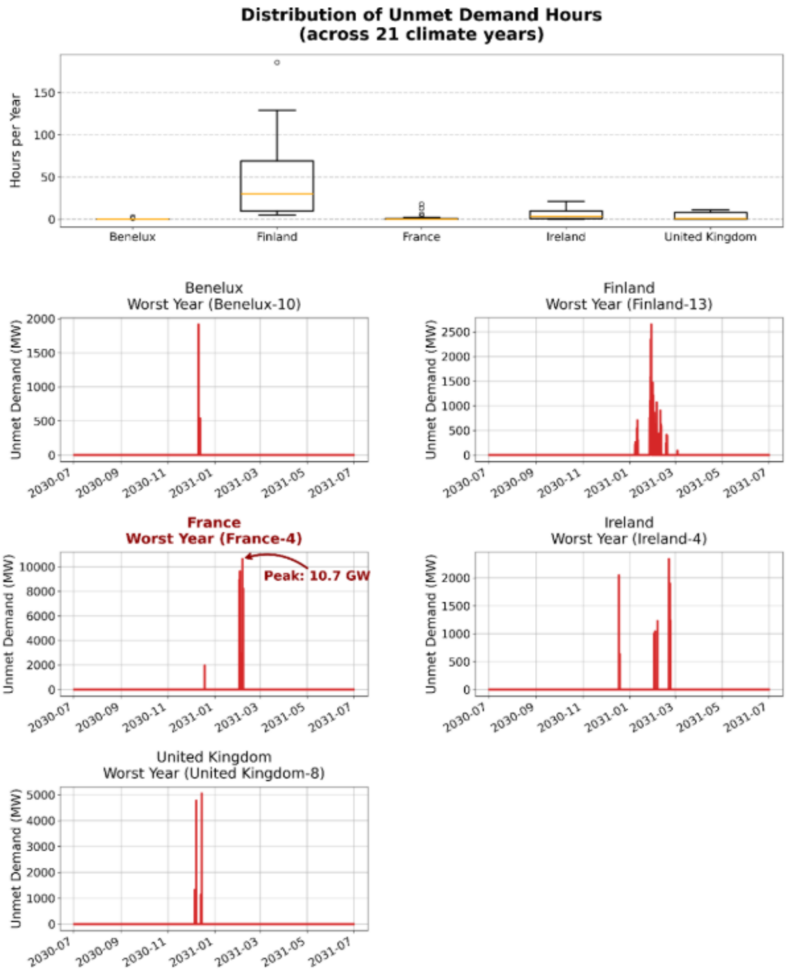
CSA7 Figure 1 shows the generation from the different technologies for France for two representative years. The generation mix and yearly demands are from the EnVIs 2060 scenarios developed in the Man0euVre project, from which we chose the NECP Essentials v1.2 scenario for the year 2030 (CETP Man0EUvRE, 2025; Barani et al., 2025; Löffler et al., 2025; Löffler, Moskalenko and Bornemann, 2025). These scenarios are still under construction and an updated version is used in the currently ongoing runs, meaning that the results presented here must only be seen as representative of the kind of figures that can be produced. It should also be noted that not all time series were available in this test run, so 'Fake' timeseries were used as replacement. The mix is characterized by a large share of nuclear power, providing a stable baseload generation. However, the significant and fluctuating contributions from wind and solar power highlight the challenges of integrating these variable renewable energy sources. The system's ability to balance supply and demand on an hourly basis is crucial, and periods of low renewable generation must be compensated by other sources, such as hydro, gas, or imports.



CSA7 Figure 2: Distribution of peak unmet demand across ensemble members. While most years show limited shortfalls, some members reveal sharp tail-risk spikes/outliers, particularly for France, where peaks can exceed 10 GW

CSA7 FIgure 2 illustrates the distribution of peak unmet demand across the different climate scenarios, highlighting the severity of potential supply shortfalls. The boxplot reveals that while many regions maintain reliability in most years, extreme climate events can drive significant spikes in unmet demand. France, exhibits a notable disparity between its average and maximum peak unmet demand, with values reaching over 10 GW in the most severe scenarios. This "tail risk" demonstrates that even well-interconnected systems with substantial baseload capacity can face acute stress periods, necessitating robust resource adequacy planning and cross-border support mechanisms to manage these extreme excursions.

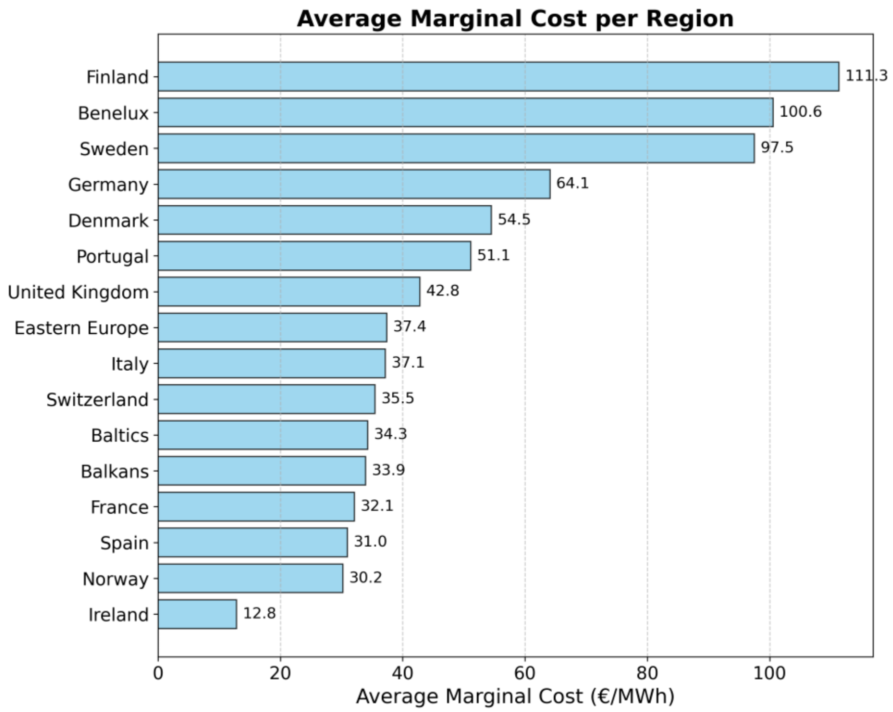


CSA7 Figure 3: The upper figure shows hours of unmet demand across the years/ensemble members. The lower figures shows the worst year/ensemble member. France stands out with sharp peaks over 10 GW, indicating particularly acute stress during the worst cases.

Building on the net balance analysis, CSA7 Figure 3 details the specific instances where supply fails to meet demand. The top panel confirms that while mean performance is often secure, significant "tail risks" of unserved energy persist across the continent. The bottom panels zoom in on the worst-case temporal profiles for the most affected regions. France's profile is particularly notable: despite a generally strong position, it faces acute, high-magnitude shortages (exceeding 10 GW) during extreme events. This concentrated deficit poses a distinct challenge compared to the more distributed shortages seen elsewhere, necessitating specific capacity mechanisms to handle these sharp peaks.

Unmet demand events were systematically identified, quantified, and characterized. The results highlight regions facing recurrent or severe shortfalls.

Marginal cost variability reflects the economic stress imposed by climate variability. Regions with limited interconnections or large shares of weather-sensitive generation experience the highest price spikes, as shown in CSA7 Figure 4 In a system with high shares of variable renewables, the ability to trade electricity with neighboring countries is essential for balancing the grid. During periods of high demand and low renewable generation in one country, imports from another can prevent energy shortages and price spikes. Conversely, surplus generation can be exported, improving the economic efficiency of the system.



CSA7 Figure 4: Average Marginal Cost per Region. This horizontal bar chart illustrates the average marginal cost of active power demand (€/MWh) across various European regions, sorted for clear comparison. It highlights the relative differences in electricity production costs.

Two primary climate-driven stress clusters are the possible drivers for this:

Summer heatwaves, combining high cooling demand, low wind conditions, and reduced thermal plant efficiency (Molina et al. 2023).

Winter cold spells, combining very high heating demand with extended low-wind periods. (Collet et al. 2025) These clusters represent critical hotspots for adequacy risk and we will undertake further analysis of the driving climate phenomena for unmet demand hours and cost peaks in the following months.

In these preliminary results it looks more possible that the latter is the case, as the most severe years/members seem to happen in winter months. However, further analyses of the final results for all models, periods and scenarios will further conclude what the most likely driver for the unmet demand is.

2.7.3. Ecosystem aspects in results

Although the plan4res modelling framework does not explicitly simulate ecosystem processes, ecological conditions exert strong and often constraining influences on electricity system performance during climate extremes. These interactions shape when and where power shortages occur, constrain the availability of generation technologies, and determine the long- term sustainability of adaptation strategies.

Hydrology and energy systems

Drought directly reduces hydropower generation by lowering reservoir inflows and river discharge. These hydrological deficits mirror ecological water stress in catchments already impacted by soil moisture depletion. Low river flows also reduce the operational flexibility of run- of- river plants, contributing to periods of reduced renewable availability precisely when demand may be elevated.

Thermal generation and cooling-water constraints

Thermal plants, whether nuclear or fossil, require sufficient river flow and acceptable water temperatures for cooling. During heatwaves, river temperatures frequently exceed environmental thresholds, reducing the permissible output of generators or forcing temporary shutdowns. These constraints reflect ecological safeguards designed to protect aquatic ecosystems from thermal stress, meaning adaptation strategies must consider both energy security and ecological integrity.

Storm impacts on forested landscapes and transmission corridors

Windstorms can damage forested areas, causing treefall onto transmission corridors and delaying repairs due to difficult terrain access. These ecosystem-mediated disruptions increase restoration times and compound power- system vulnerability when storms coincide with other climate hazards. Vegetation management and resilient corridor design become essential adaptation measures.

Other direct and indirect impacts could be considered, however as the plan4res model is not directly given information that can support conclusions in these aspects it would require future work to look more specific on the impacts on ecosystems.

2.7.4. Assessment of Societal and Human Vulnerabilities

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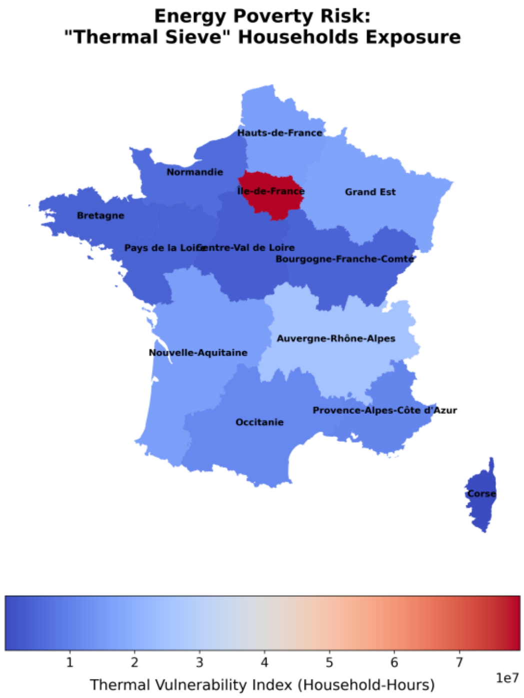
Climate-driven electricity shortages do not translate uniformly across society. Instead, their impacts depend on demographic, infrastructural, and socio-economic characteristics that shape both exposure and sensitivity to outages. To capture these differences, three complementary vulnerability indicators were assessed: thermal vulnerability, industrial exposure, and urban heat vulnerability.

Thermal Vulnerability

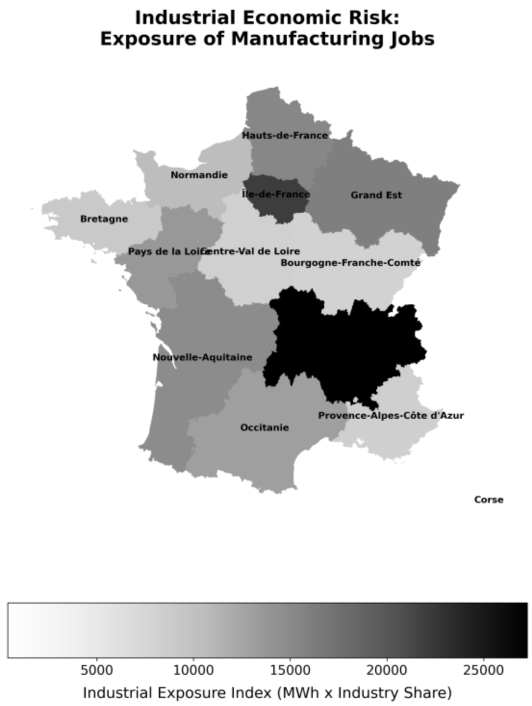
Thermal vulnerability reflects the proportion of households living in poorly insulated dwellings, which can experience rapid and hazardous indoor temperature changes when electricity for heating or cooling is interrupted. Regions with high shares of F- and G-rated homes face amplified risks during both cold spells and heatwaves. CSA7 Figure 5 is showing a map of ADM1 regions in France with high "thermal sieve" household exposure. It is highlighting regions where a large proportion of homes are poorly insulated and thus more vulnerable to temperature extremes during power interruptions. The darker or redder areas on the map indicate regions with the highest thermal vulnerability, meaning those areas are at greater risk during heatwaves or cold spells if there's an electricity shortage. The data set is retrieved from ONRE (Observatoire National de la Rénovation Énergétique) / SDES (Service des données et études statistiques), calculating the share of F and G rated dwellings by region.



CSA7 Figure 5: This map illustrates the region distribution across ADM1 regions in France, highlighting areas with high "thermal sieve" household exposure. Thermal vulnerability reflects the proportion of households living in poorly insulated dwellings (F- and G-rated homes).

Industrial Exposure

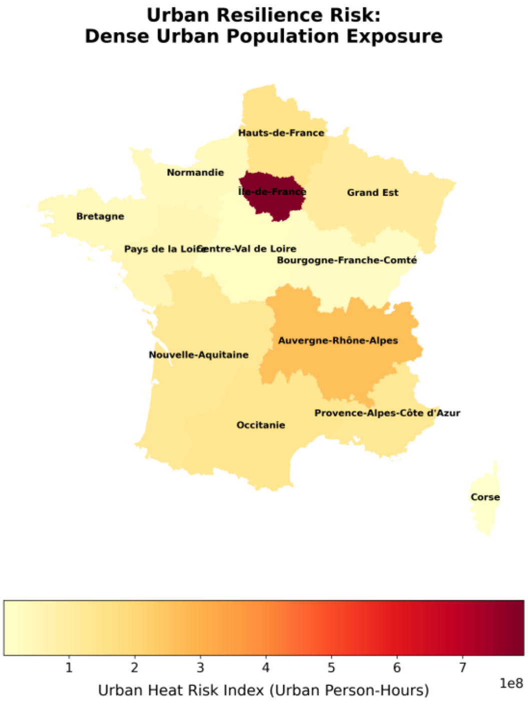
Industrial exposure captures the concentration of employment in manufacturing and energy-intensive sectors. Power outages in these regions can trigger significant economic losses, production interruptions, and cascading supply-chain disruptions. Regions with large industrial bases are therefore more sensitive to even short-duration electricity shortages. CSA7 Figure 6 shows the percentage of regional workforce employed in the industrial sector for each domain, making the assumption that people employed in industry work in their home region. The data is obtained from INSEE (Institut national de la statistique et des études économiques) and indicates that especially in the Auvergne-Rohne-Alps regions is there a large share of industry leading to higher economic risks in relation to both energy shortage and higher electricity costs.



CSA7 Figure 6: This map shows regional industrial economic risk, reflecting concentrated manufacturing and energy-intensive employment (INSE data). Darker areas, like Auvergne-Rhône-Alpes, signify higher vulnerability to economic losses from energy disruptions.

Urban Heat Vulnerability

Urban heat vulnerability represents the risks faced by densely populated metropolitan areas when power is lost during heatwaves. Loss of cooling, public transport constraints, and heat island amplification can combine to create severe public health risks. Vulnerable populations include the elderly, infants, those with chronic illnesses, and individuals with limited ability to relocate or access alternative cooling resources. CSA7 Figure 7 shows a calculation of the percentage of the population in each region that live in urban clusters versus in rural areas and therefore is here used as a proxy for the urban heat island effect sensitivity. The data is obtained from INSEE specifically the “Population municipale des unités urbaines” (Base des unités urbaines 2020) data set.



CSA7 Figure 7: This map shows urban heat vulnerability across French ADM1 regions. It highlights risks to densely populated areas during heatwaves with power loss, affecting vulnerable groups due to lack of cooling and amplified heat island effects. The map uses the percentage of regional population in urban clusters (INSEE data) as a proxy for this sensitivity.

Combined Vulnerability Insights

Integrating these indicators shows that societal risk is not solely a function of the magnitude of electricity shortages. Some regions exhibit high vulnerability due to socio-economic profiles and demographic factors. Conversely, regions with more resilient infrastructure and lower exposure may tolerate larger shortages with comparatively lower societal impact. This underscores the need for risk frameworks that combine physical system performance with social vulnerability to identify where climate-driven power system stress is likely to translate into human harm. We will further assess and calculate risks for the different scenarios and by comparing these with the baseline run of the model be able to estimate the difference in risks for the different climate scenarios and future periods.

Capabilities Impacted

CSA7 Table 1 presents a capability-based overview of how power system stress affects human wellbeing. It links key capabilities to their associated impacts, relevance for vulnerable contexts, potential influence through policy or system measures, and indicative metrics for assessment.

CSA7 Table 1: Capability-based overview of power system stress impacts.

Capability	Nussbaum´s categories	Functioning	Wellbeing	Relevance	Influenceability	Indicator (qualitative/ quantitative) for measuring capabilities*
Being able to maintain a healthy and safe indoor temperature (Thermal Comfort).	Bodily Health	Staying warm during winter cold spells or cool during summer heatwaves despite power grid stress.	Basic needs	High relevance for households in "passoires thermiques" (energy class F/G). Power outages during cold snaps render electric heating useless, causing immediate health risks in poorly insulated homes.	Can be influenced by housing renovation policy (insulation), targeted social tariffs, or priority grid restoration for vulnerable districts.	Thermal Vulnerability Index (Vulnerable Household-Hours)
Being able to work and hold property (Economic Stability).	Control over one's Environment (Material)	Maintaining employment and industrial productivity without interruption from forced load shedding.	Living conditions	Power shortages may force industrial curtailment, risking jobs and economic stability in heavily industrialized regions (e.g., Grand Est, Auvergne-Rhône-Alpes).	High. Demand-side response mechanisms, industrial battery storage, and cross-border energy trading improvements.	Industrial Exposure Index (Unmet MWh weighted by Industrial Employment Share).
Being able to live safely in high-density urban environments.	Bodily Integrity / Control over one's Environment	Accessing ventilation, air conditioning, and functioning urban infrastructure (water pumps, transit) during summer heatwaves.	Living conditions	Dense urban areas (e.g., Paris/Île-de-France) rely heavily on electricity to mitigate the "Urban Heat Island" effect. Power failure during a heatwave significantly degrades livability.	Passive urban cooling (greening), reduced reliance on active cooling, and resilient urban grid design.	Urban Heat Risk Index (Urban Person-Hours of Unmet Demand).

2.7.5. Synthesis and Priorities for Action

The ensemble-based assessment reveals that climate-driven stresses on the power system arise from the interaction of meteorological variability, system design constraints, cross-border dependencies, and societal vulnerabilities. The following synthesis identifies the core patterns of risk emerging from the analyses and outlines corresponding priorities for action.

Climate- robust generation portfolios

Periods of low renewable output underscore the importance of diversifying generation portfolios with technologies less sensitive to climatic conditions. This includes expanding storage, reinforcing hydropower resilience, and maintaining firm capacity that can operate under elevated temperatures and reduced cooling-water availability for nuclear power plants.

System flexibility and demand response

A recurring feature of the ensembles is the clustering of unmet demand during short, high- stress periods. Enhancing flexibility, via storage expansion, demand- response programmes, and improved forecast- driven operational strategies could help in reducing peak stress and mitigates shortage events lowering the general risks.

Socially targeted resilience strategies

Regions with high thermal vulnerability, dense urban populations, or large concentrations of energy- intensive industries experience disproportionately high impacts during outages. Targeted policies such as building retrofits for low- income households, urban cooling strategies, and continuity planning for industrial clusters increase societal resilience. Ultimately helping protecting both the economy and the communities that depend on them.

Strengthened cross- border coordination

The adequacy of France and its neighbours is strongly shaped by interconnector availability and the simultaneity of climate impacts across countries. Pan- European adequacy stress- testing, coordinated reserve planning, and strategic investment in transmission corridors are required to manage shared risks during regional climate extremes.

2.8. #8 SPILLOVER (Global Agriculture)

2.8.1. Summary of Key Risks from D2.2

Case Study 8 examines how climate-induced changes in agricultural productivity propagate across regions through economy-wide production, trade, and competitiveness linkages. According to the D2.2 model simulations, climate change generates asymmetric and system-wide impacts on global agriculture, with temperature-driven yield shocks propagating through production systems, trade patterns, and regional welfare outcomes. Projected warming leads to widespread reductions in crop yields across most regions, with the magnitude and direction of impacts varying strongly by crop, region, and warming scenario. Model results for 2050 under SSP2-4.5 and SSP5-8.5 show widespread declines in rice and wheat production across most regions, while gains in cereals and other crops are largely confined to high-latitude regions with colder baseline climate conditions.

Beyond direct production effects, the D2.2 simulations show that climate induced productivity shocks propagate through endogenous price, trade, and competitiveness adjustments that shape economy-wide outcomes and influence the distribution of risks across regions. Climate induced productivity losses translate into asymmetric price and trade responses that reallocate market shares and income across regions by altering relative production costs, export performance, and access to international markets. In regions experiencing pronounced productivity declines, local production contracts and prices increase, reducing export competitiveness. Exports contract more sharply than local production as pressures are transmitted through international markets. These trade adjustments extend beyond exporting regions to their trading partners, as price transmission and changes in import sourcing alter the distribution of climate impacts across countries linked through food supply chains. At the same time, regions experiencing relatively favourable productivity outcomes expand exports and capture market share vacated by climate affected producers, with export growth exceeding production growth. Taken together, these mechanisms indicate that climate impacts are transmitted internationally through trade and supply-chain linkages, leading to a redistribution of income and welfare that reflects regions' integration into global markets rather than only their local climate exposure.

2.8.2. Supplementary issues related to D2.2.

While D2.2 provides a comprehensive assessment of climate spillovers transmitted through agricultural yield and land productivity, it does not capture heat-induced reductions in labour productivity in agriculture and other economic sectors. Heat stress caused by climate change affects labour input efficiency and propagates to production, trade, and income outcomes across regions (Orlov et al., 2020, Dasgupta et al., 2024). As a result, the assessment emphasises land- and crop-based climate risks, while abstracting from constraints on effective labour input that may independently shape production costs, sectoral value added, and competitiveness under rising temperatures. The extended analysis addresses this gap by explicitly assessing climate-induced impacts on labour productivity across sectors and regions, and by examining how these impacts translate into distributional and poverty outcomes through global economic and trade linkages.

Heat stress reduces labour productivity by constraining work intensity and hours, thereby lowering effective labour input across the economy rather than affecting a single production factor or sector (Kjellstrom et al., 2009; Parsons et al., 2021). Unlike yield-based shocks, which originate in specific agricultural activities and are transmitted through downstream adjustments, labour productivity losses apply simultaneously across agriculture, manufacturing and service sectors, directly affecting value added wherever labour is used in production. This economy-wide reduction in labour efficiency constrains economic activity and alters relative production costs and income generation across sectors and regions, and its effects are compounded through intersectoral linkages as changes in labour input propagate via input–output relationships and price adjustments.

Labour productivity losses have inherently distributional consequences, as they operate through labour earnings and employment and are therefore inseparable from the assessment of poverty and income distribution outcomes. Reductions in labour productivity led to declines in output, labour income and employment, with particularly pronounced effects in regions where household incomes are labour based. These income-driven effects are not fully reflected in aggregate welfare measures, which are based on a representative household and therefore do not capture poverty outcomes explicitly. Linking the ENGAGE model to a global poverty module (GlobPov) enables changes in average income and prices induced by labour productivity shocks to be translated into poverty indicators, thereby making explicit the distributional implications that remain unobserved in representative-household welfare measures.

2.8.3. Assessment of Societal and Human Vulnerabilities

Climate-induced labour productivity losses do not translate uniformly into economic, societal and human outcomes. Their impacts depend on regional economic structures, factor income composition, and patterns of intersectoral linkages and international trade that determine how productivity losses are transmitted through production, prices, and incomes. From a spillover perspective, vulnerability therefore reflects not only local exposure to heat stress, but also the extent to which regions are economically connected to affected sectors and trading partners, and the degree to which households rely on labour income and essential goods whose prices respond endogenously to economy-wide adjustments.

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Productivity shocks

Rising temperatures reduce the efficiency of workers across the entire economy limiting work capacity through heat stress, which lowers labour productivity across a wide range of activities (Dasgupta et al., 2024; Knittel et al., 2020). Empirical evidence shows that effects are not confined to specific sectors, but apply broadly across agriculture, manufacturing, and services (Roson & Sartori, 2016).

As illustrated in CS8_Figure 1, the magnitude of labour productivity losses exhibits a consistent increase with higher levels of warming, with higher temperature scenarios (SSP5-8.5) exhibiting stronger productivity declines than moderate warming (SSP2-4.5). The global surface temperature is expected to increase to approximately 2.0 °C under the SSP2-4.5 scenario and 2.4 °C under the SSP5-8.5 scenario. Sectoral variations in the magnitude of labour productivity losses reflect assumed differences in heat exposure and work intensity embedded in the underlying damage functions, with the largest impacts observed in agriculture followed by manufacturing and services[1].

Within the computable general equilibrium (CGE) framework, negative labour productivity shocks reduce the efficiency of the labour endowment across the various production activities, propagating through the economy via reduced output, economic activity and household income. While lower productivity places upward pressure on production costs, the simultaneous reductions in household purchasing power dampen aggregate demand. As heat stress reduces labour productivity across all sectors and regions, it is expected to cause widespread declines in regional output and income.

[1] The agriculture sector includes paddy rice, wheat, cereal grains not elsewhere classified, and other crops. The manufacturing sector comprises agriculture and food processing, minerals, paper, chemicals, non-metallic minerals, iron and steel, metal products, other industry, coal, crude oil, gas, and petroleum and coke. The services sector includes nuclear power, coal-fired power, gas-fired power, oil-fired power, hydroelectric power, wind power, solar power, other power generation, transmission and distribution, services, and transport.

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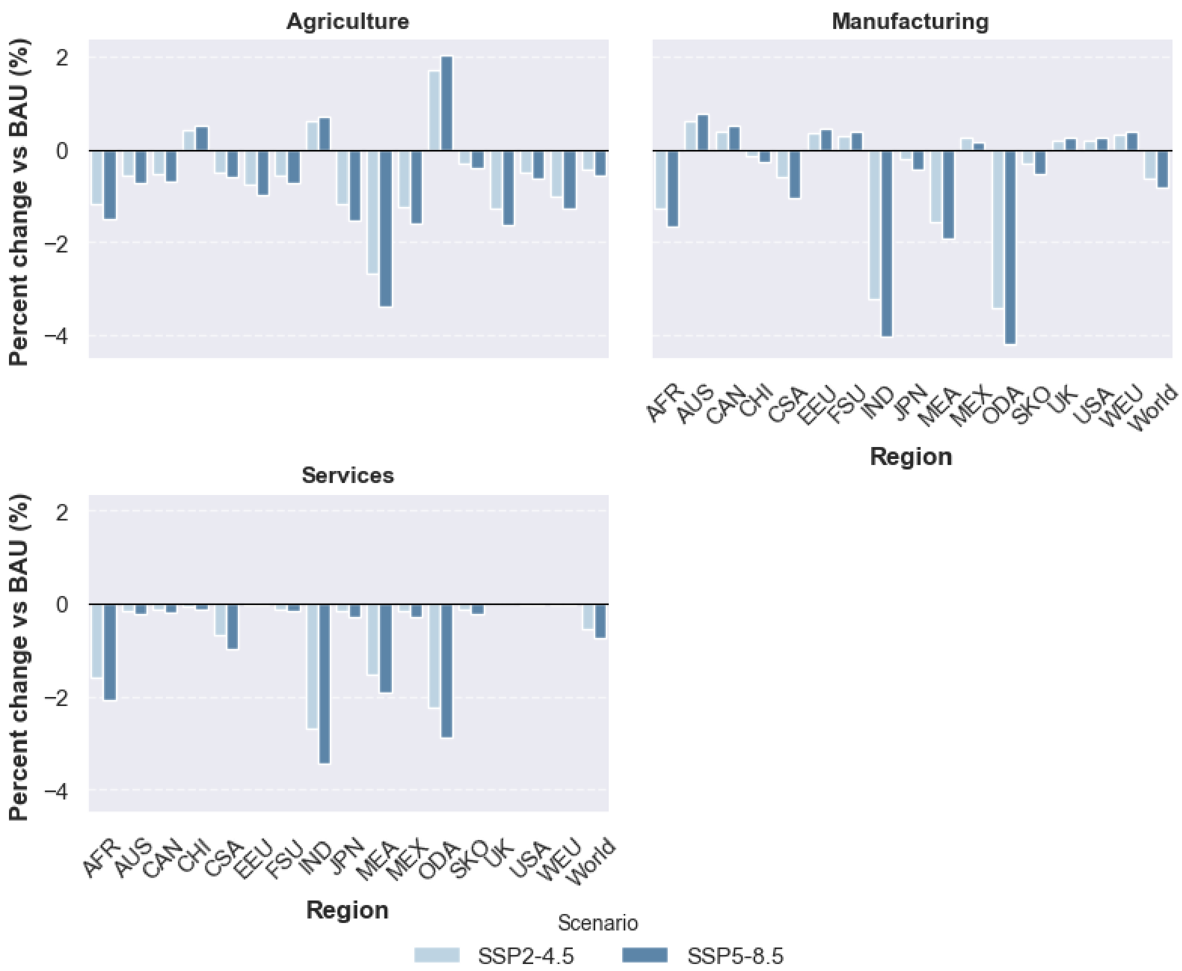
CS8_Figure 1: Climate-induced labour productivity shocks by sector, region, and warming scenario. The figure shows expected reductions in labour productivity across agriculture, manufacturing, and services under SSP2-4.5 and SSP5-8.5, reflecting heat-stress-induced constraints on labour input. Africa (AFR), Australia (AUS), Canada (CAN), China (CHI), Central and South America (CSA), Eastern Europe (EEU), the Former Soviet Union (FSU), India (IND), Japan (JPN , the Middle East (MEA), Mexico (MEX), Other Developing Asia (ODA), South Korea (SKO), the United Kingdom (UK), the United States (USA), and Western Europe (WEU), and the global aggregate (World).

Sectoral Output

The widespread decline in labour productivity leads to a broad-based reduction in economic activity across all sectors, lowering output in agriculture (AGR), manufacturing (MAN), and services (SER). As labour efficiency declines, the contribution to output per unit of labour falls, constraining production across the whole economy. The global production of agriculture, manufacturing and services declines, and these declines becomes more pronounced under the stronger warming scenario (SSP5-8.5) (CS8_Figure 2). The widespread decline in economic activity results in a decline in labour income which feeds back into the economy through reduced household consumption demand, further dampening output across sectors. The magnitude of sectoral output losses increases with the severity of warming, with the higher-warming scenario (SSP5-8.5) generating larger sectoral output losses compared to the lower emission scenario (SSP2-4.5).

The impact of labour productivity losses on output varies across sectors, reflecting differences in labour intensity and the scope for substituting labour with other production inputs. Agriculture experiences the largest output declines due to its higher exposure to outdoor working conditions and greater sensitivity of labour productivity to temperature increases, while manufacturing and services exhibit smaller average impacts consistent with lower work intensity thresholds and greater scope for mitigating heat exposure.



CS8_Figure 2: Percentage change in sectoral output relative to the business-as-usual baseline by region, sector and warming scenario. Africa (AFR), Australia (AUS), Canada (CAN), China (CHI), Central and South America (CSA), Eastern Europe (EEU), the Former Soviet Union (FSU), India (IND), Japan (JPN , the Middle East (MEA), Mexico (MEX), Other Developing Asia (ODA), South Korea (SKO), the United Kingdom (UK), the United States (USA), and Western Europe (WEU), and the global aggregate (World).

Production impacts also vary across regions, reflecting differences in economic structure, sectoral composition, and exposure to rising temperatures (CS8_Figure 2). Regions such as Africa, India, the Middle-east and Other Developing Asia with a higher share of labour-intensive activities or greater exposure to heat stress experience more pronounced output declines, while regions such as Canada, the USA and Western Europe with more diversified production structures or lower temperature increases exhibit relatively smaller impacts.

These regional differences are further shaped by intersectoral and trade linkages, which transmit productivity shocks across borders and redistribute production responses through changes in competitiveness, import demand, and export performance.

Trade

The impact of climate change on labour productivity is highly heterogenous across regions and sectors (CS8_Figure 1). These disparities reshape regional comparative advantages in the production of goods and services, triggering adjustments in trade patterns and income distribution at a global scale. CS8_Figure 3 show that in many regions sectoral production increases modestly, but export growth is even more pronounced (most observations are above the red line), indicating that favourable production conditions translate into competitive gains in international markets. Regions less affected by heat stress leverage their relative better position expanding production and capturing market shares vacated by climate-stressed producers, with export growth often outpacing domestic production. At the same time, regions facing severe heat stress experience sharp contractions in both production and exports, with exports losses exceeding domestic production (most observation are below the red line). Their decline in production erodes competitiveness and trade linkages amplify these effects. These asymmetric responses underscore how climate-induce productivity shocks propagate through global supply chains, redistributing market shares, income and welfare in ways that depend not only on local climate exposure but also on the degree of integration into international markets.

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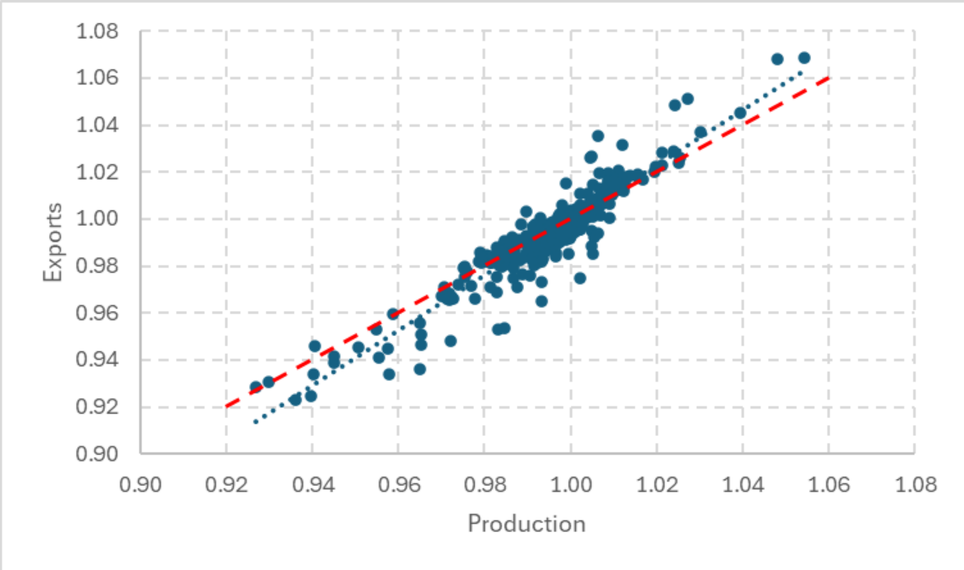

CS8_Figure 3: Relative change in sectoral production and exports in 2050 under the high-emissions SSP5-8.5 scenario. Relative change with respect to the business-as-usual baseline. Each dot represents a combination of a sector and region. The blue dotted line represents the linear trend and the red segmented line a situation where the change in production is proportional to the change in exports.

GDP and Welfare

Reductions in labour productivity translate into adverse macroeconomic outcomes across all regions, reflected in declines in both GDP and household welfare relative to the business-as-usual baseline. As labour productivity declines, aggregate production falls, leading to lower value added and reduced economic activity. These GDP losses intensify under higher warming (SSP5-8.5), as stronger temperature increases generate larger productivity shocks and amplify the contraction in output across sectors.

Welfare impacts are generally more pronounced than GDP effects, reflecting the combined influence of income and price adjustments on household real purchasing power. In the CGE framework, welfare captures changes in real income rather than production alone and therefore responds not only to reduced labour earnings but also to shifts in consumer prices induced by economy-wide adjustments. As a result, regions experiencing relatively modest GDP declines may nonetheless face sizeable welfare losses when labour income reductions coincide with unfavourable price movements.

The magnitude of GDP and welfare impacts varies substantially across regions, highlighting the uneven distribution of labour productivity shocks through the global economy (CS_8 Figure 4). Regions with higher exposure to heat stress and greater reliance on labour-intensive activities, such as

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Africa, India, and Other Developing Asia, experience larger declines in both GDP and welfare. In contrast, regions with more diversified production structures, lower average exposure to heat stress, or stronger integration into global markets tend to exhibit smaller aggregate losses. These differences underscore the role of economic structure and factor income composition in shaping regional vulnerability to climate-induced labour productivity shocks.

In several regions, welfare losses exceed GDP losses, indicating that the distributional consequences of labour productivity shocks extend beyond aggregate production effects. This pattern reflects the central role of labour income in household earnings and the limited ability of households to fully offset income losses through substitution or price adjustments. The divergence between GDP and welfare responses highlights the importance of assessing societal impacts using metrics that capture real income effects, rather than relying solely on output-based indicators.

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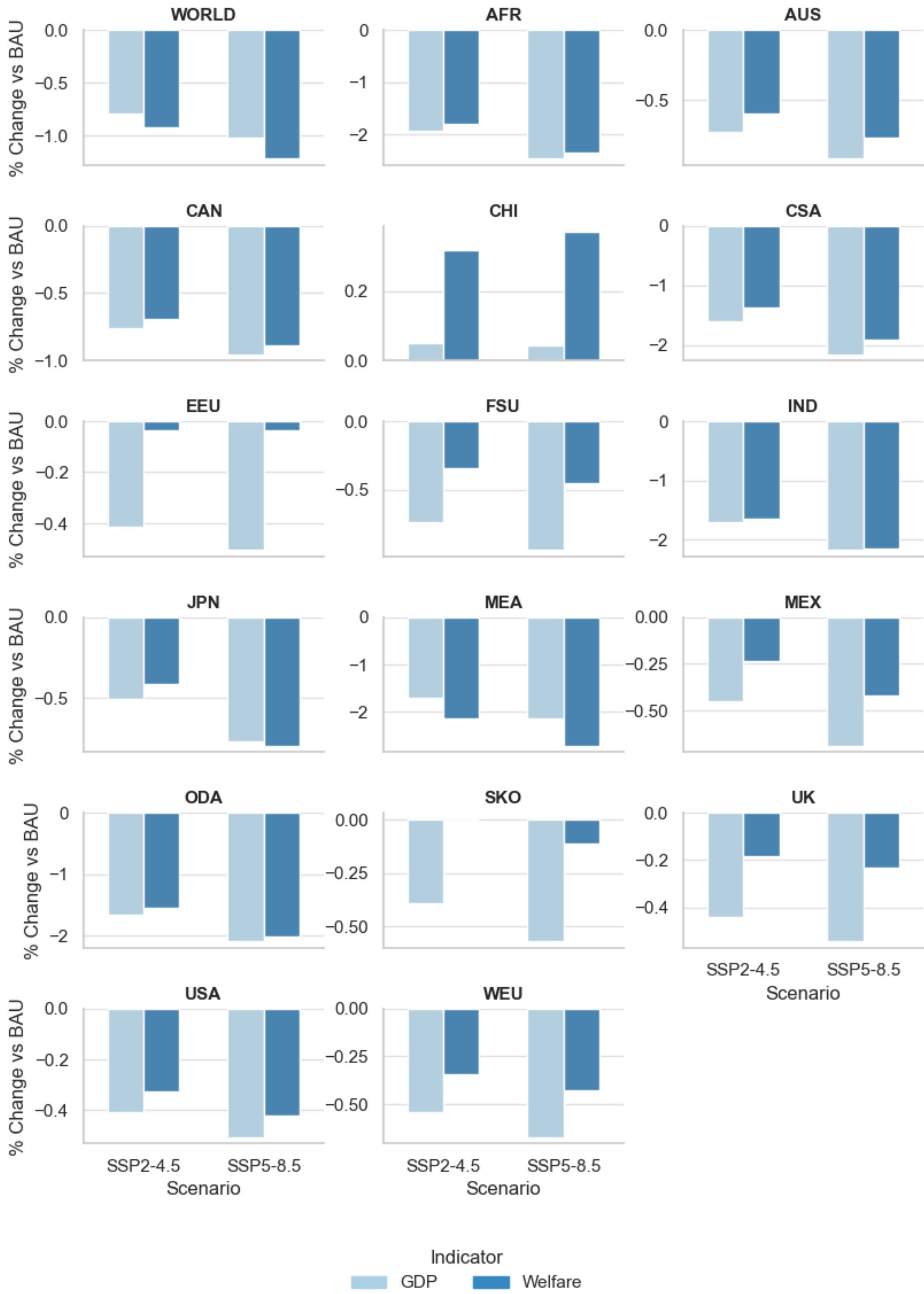


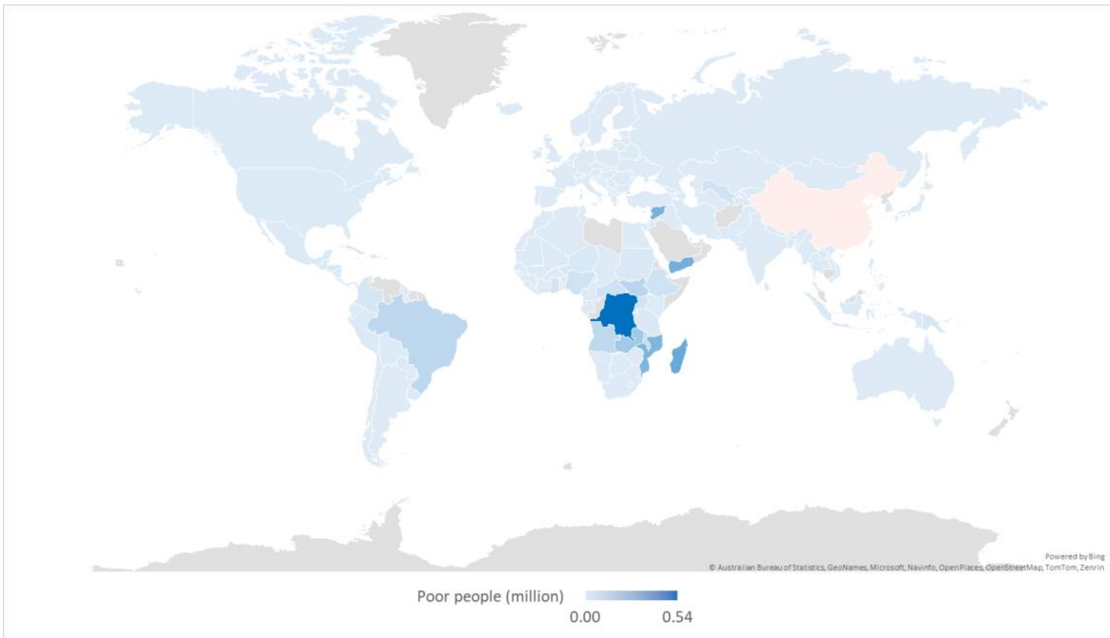
CS8_Figure 4: Regional impacts on GDP and welfare under climate-induced labour productivity shocks. The figure shows percentage changes in regional GDP and household welfare relative to the business-as-usual baseline under the SSP2-4.5 and SSP5-8.5 scenarios. Results are reported for Africa(AFR), Australia (AUS), Canada (CAN), China (CHI), Central and South America (CSA), Eastern Europe (EEU), the Former Soviet Union (FSU), India (IND), Japan (JPN), the Middle East (MDE), Mexico (MEX), Other Developing Asia (ODA), South Korea (SKO), the United Kingdom (UK), the United States (USA), and Western Europe (WEU).

Poverty

The slowdown in economic activity induced by climate change-related labour productivity losses risks undermining progress in poverty reduction. Reduced labour productivity leads to lower labour demand and wages, which compress household incomes and ultimately diminish real purchasing power, particularly among households that rely predominantly on wage earnings.

Poverty outcomes reflect the aggregate effects of economy-wide labour productivity losses transmitted from labour markets into domestic commodity markets and ultimately into international markets. Under the SSP5-8.5 scenario, global extreme poverty might increase by 5%, rising from 49.9 to 51.4 million people. This increase reflects the cumulative effects of labour income losses, which disproportionately affects households near the poverty threshold and limit their ability to absorb income shocks.

At the regional level, poverty impacts are unevenly distributed and shaped by structural economic characteristics and exposure to labour productivity losses (CS8_Figure 5). Regions with high reliance on wage income and greater exposure to heat stress experience more pronounced increases in extreme poverty, as compared to regions with higher income levels. Extreme poverty increases mainly in tropical regions in Sub-Saharan Africa, the Middle-east and Brazil.



CS8_Figure 5: Spatial distribution of changes in the population living in extreme poverty under climate-induced labour productivity shocks in 2050 under the SSP5-8.5 scenario. The map shows changes in the number of people living in extreme poverty (in millions) across world regions.

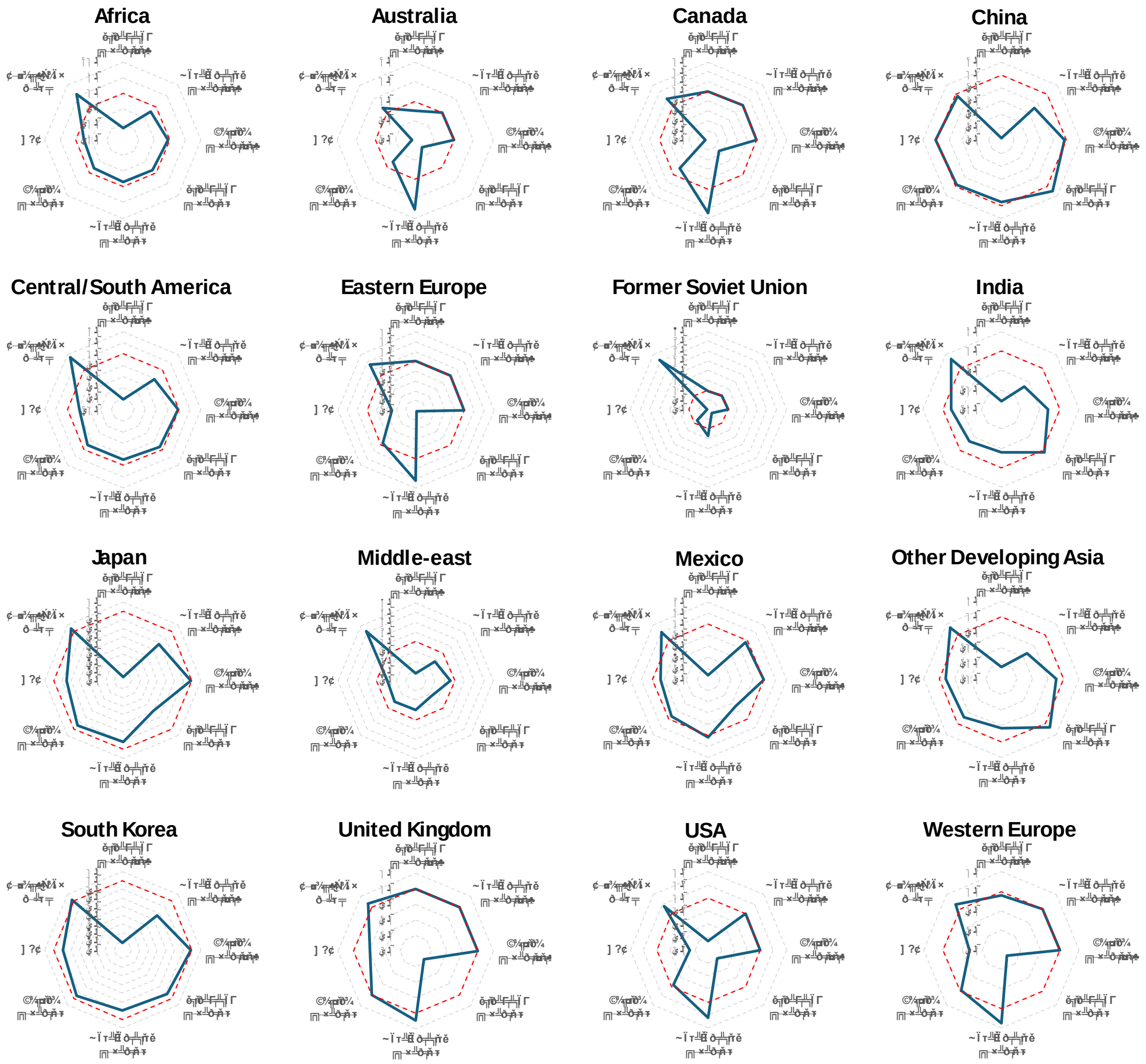
Risk analysis for SSP5-8.5

Under SSP5-8.5, climate-induced labour productivity losses translate into heightened economic risks across regions through simultaneous impacts on production, income, and welfare-related outcomes. CS8_Figure 6 illustrates the simultaneous adverse physical and economic risks across labour productivity, sectoral output, GDP, and distributional outcomes captured through extreme poverty headcount measures across regions.

The combined response of these indicators highlights substantial heterogeneity in regional risk profiles, with several regions experiencing declines in labour productivity, sectoral output, and aggregate income alongside rising poverty. Africa, India, and Other Developing Asia emerge as the most exposed regions, with declines across nearly all indicators. In these regions, productivity losses are accompanied by broad-based contractions in sectoral output and GDP, alongside marked increases in poverty headcounts, indicating elevated compound risk under SSP5-8.5.

Intermediate risk profiles are observed in regions such as Central and South America, the Middle East, Easten Europe and the Former Soviet Union, where labour productivity and sectoral output losses are evident but translate less uniformly into poverty outcomes.

By contrast, Western Europe, North America, Japan, South Korea, Australia, and China display comparatively narrower risk profiles. Although productivity losses and sectoral output declines are present, impacts on GDP are smaller and poverty outcomes remain largely unchanged.



CS8_Figure 6: Regional physical and economic risk profiles in 2050 under SSP5-8.5. Radar plots show percentage deviations from the baseline associated with climate-induced labour productivity losses under the high-warming scenario (SSP5-8.5), across agricultural, manufacturing, and services productivity and output, as well as aggregate GDP and extreme poverty headcount. The segmented red line indicates no change in the corresponding indicator.

Capabilities Impacted

Under SSP5-8.5, heat-induced labour productivity losses reduce labour incomes, constraining households' ability to meet basic nutritional needs, with disproportionate impacts on labour-dependent and low-income households. As real incomes decline, access to sufficient and affordable food deteriorates, linking climate-induced productivity shocks to risks in health and nutrition.

At the same time, rising temperatures impair work capacity and reduce labour efficiency across sectors. These constraints translate into lower wages, reduced employment, and heightened exposure to unsafe working conditions, weakening the capability to participate in secure and dignified economic activity rather than affecting employment outcomes alone.

Beyond labour markets, productivity losses propagate through the economy reducing economic activity, as well as household income, consumption and welfare. In regions with limited income diversification, the erosion of purchasing power undermines the ability to sustain adequate housing and stable living conditions, signalling broader declines in living standards under high-warming conditions.

CS8_Table 1: Description of capabilities impacted by heat stress impacts on labour productivity.

Capability	Nussbaum´s categories	Functioning	Wellbeing	Relevance	Influenceability	Indicator (qualitative/ quantitative) for measuring capabilities*
Being able to have good health and be adequately nourished	Bodily Health	Access to sufficient food and income to maintain nutrition and health.	Basic Needs	Heat-induced labour productivity loss reduces household income and raises food prices, lowering nutrition and welfare.	Productivity improvements, adaptation investments, income transfers, or trade adjustments.	Percentage change in household real income; food production, food prices; food trade
Being able to work in safe and dignified conditions	Control over One's Environment (Material)	Secure and sustainable employment without health or income loss.	Living Conditions	Heat stress reduce labour productivity, wages, and employment.	Capital–labour substitution, mechanisation, improved working conditions, sectoral adaptation policies.	Percentage change in sectoral employment, wages and productivity
Being able to have adequate shelter and stability of living conditions	Bodily Health / Material Control	Maintain stable income and living standards under climate stress.	Living Conditions	Heat-induced labour productivity loss lowers disposable income and welfare, especially	Productivity improvements, adaptation investments, income transfers.	Percentage change in household consumption; real income (welfare); GDP.

				in vulnerable regions.		

2.8.4. Synthesis and Priorities for Action

The analysis indicates that climate-induced labour productivity losses generate adverse economic impacts across regions under both SSP2-4.5 and SSP5-8.5, with higher warming intensifying the magnitude of these impacts. Across scenarios, productivity losses translate into reductions in sectoral output, GDP, and welfare, but the extent to which these effects accumulate and propagate varies substantially across regions.

The analysis demonstrates that similar labour productivity shocks can give rise to very different welfare outcomes depending on regional economic structures and transmission mechanisms. Widespread productivity shocks not only reduce sectoral production and overall economic activity, but also lowers labour incomes, leading to a contraction in household consumption and further reinforcing output declines beyond the initial productivity effect. As reduced incomes and price adjustments propagate through the economy, the consequences become increasingly evident in welfare and poverty outcomes, particularly in regions where households rely heavily on labour earnings. This synthesis suggests that priorities for action should be guided primarily by where labour productivity losses translate into welfare and poverty impacts, rather than by sectoral output or GDP effects alone.

3. Assessing Climate Impacts on socioeconomic dimensions and Human Capabilities in the case studies

Assessing climate impacts on socioeconomic dimensions needs an integrated framework that can help in understanding the impacts of climate events on human well-being and social equity, moving beyond pure asset damage. An important step in this is linking physical impacts (the hazard itself) with social impacts (the resulting consequences on people and systems), which is highly relevant for prioritising and designing effective adaptation projects. See more details on this in D2.1.

The case studies include assessment of climate impacts on socioeconomic dimensions and human capabilities and table 1 below summarises the societal, human and gender dimensions addressed in the case studies

Table 1: Overview of the societal, human and gender dimensions addressed in case studies

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Case studies	Societal and Human Vulnerability Focus	Key Human impact dimensions and capability Constraints
# 1 HEAT	Heat-related mortality and increased health burden due to population aging. Women are identified as a high-risk group for heat-related mortality. Heat Prevention Plans reduce the risk of heat-related mortality across Europe	Bodily Health: Premature mortality and morbidity due to extreme temperatures.
#2: DROUGHT	Socio-economic risks of drought, competition for resources, and agricultural net benefits.	Control over one's Environment: Loss of livelihood and resources due to crop failure and resource competition.
#3: STORM	Coastal flooding impacts, Equity-adjusted costs focusing on low-income households.	Control over one's Environment/Shelter: Property damage, risk of displacement, and disproportionate financial burden on vulnerable groups.
#4: FLOOD	Monetization of M&A benefits and equitable distribution of these benefits. WTP for flood mitigation was explicitly analyzed by gender and income groups.	Control over one's Environment/Shelter: Ability to move freely and access to essential services, to live in safe housing
#5: SNOW	Changing avalanche hazard conditions reflected in potential risk to communities and sensitive sectors (tourism, transport, and forestry) under future climate change.	Bodily Integrity: Risk to life and safety; Play/Leisure: Impact on tourism and associated livelihoods.
#6: INDIRECT (Lower Danube)	Cross-sectoral impacts of multi-hazards (floods/droughts) under socio-economic vulnerability. Female-majority households are noted as having less capacity to recover from property damage.	Control over one's Environment: Reduced capacity to recover from property damage due to pre-existing social vulnerability.
#7: INDIRECT (Power System)	Quantifying the cost of adaptation for a renewable-dominated electricity system under concurrent extremes.	Basic Needs: Interruption of power supply (internet, heat, light) and high cooling/heating demand in summer/winter.

#8: SPILLOVER	Global impacts on crop yields, trade, and regional economies, widening the global equity gap.	Material Needs: Reduced crop yields and welfare in tropical regions; global equity and food security impacts.

The assessment across the 8 case studies (CSAs/STLs) leveraged a variety of novel impact data to add social dimensions of climate risks, which is adding key information to economic damage cost estimates:

- Quantitative impact data via the capability approach: The case study analysis quantified further dimensions than what is included in monetary damage estimates of climate events. For the Storm case study (CS3) (Aabenraa and Haderslev), survey data provided measurable time burdens on individuals, revealing a substantial hidden cost: Haderslev residents reported an average of 271 hours spent on property restoration, the equivalent of over six full-time weeks of unpaid labour, indicating a heavy toll on household well-being and capability. For CS5, the direct impact of snow avalanches is expressed by the fatalities reported in the official inventories (e.g., European Avalanche Warning Service – EAWS, the Institute for Snow and Avalanche Research – SLF, regional avalanche warning services in Austria – LWDs, International Commission for Alpine Rescue – ICAR, International Association for Coordination and Documentation of Snow and Avalanche Problems – AINEVA, Salvamont Romania).
- Socio-demographic disparities and vulnerability: Impact data was disaggregated to expose social inclusion issues. The Heat case study (CS1) confirmed that while regional wealth was not the main driver of risk, individual characteristics—age, marital status, and chronic illness—were the most significant determinants of heat-related mortality and morbidity risk. The Flood case study (CS4) showed that in the Triveneto area, psychological stress was the single most frequently reported flood-related impact (37.24% of affected respondents), demonstrating the acute non-physical impact. Disaggregation further revealed that women were significantly more likely to report emotional distress than men. For CS5, vulnerability is expressed as a ratio between sensitivity (through the EUROSTAT NUTS 3 indicators S1 – nights spent per capita, S2 – Gross Domestic Product at current market prices and S3 – average time to the nearest hospital) and adaptive capacity (maturity of national snow avalanche early warning systems and risk monitoring)
- Perceived risks and institutional trust: Qualitative data from citizen surveys and stakeholder workshops (CS1-CS6) provided critical metrics on the non-technical aspects of resilience. For Drought (CS2), respondents in Romania perceived a higher impact on capabilities than those in Czechia and Poland, most prominently noting a

diminished attractiveness of the landscape, affecting the capability to enjoy recreational activities. For Flood (Triveneto, CS4), the survey revealed that despite generally favourable trust in local institutions, a large share of citizens expressed a limited understanding of institutional roles and low confidence in flood-related policies, indicating a fragmented governance landscape. For Snow (CS5), there is a completely different picture. In the Alpine region, stakeholders report high trust in well-established institutions and forecasting systems, supported by long-standing risk governance and advanced monitoring. In contrast, in the Carpathian countries, limited institutional capacity, fragmented responsibilities, and limited data availability translate into weaker institutional trust and lower perceived avalanche risk, reinforcing gaps in preparedness and effective risk management.

- Systemic failures and adaptation gaps: The Indirect (Power System) case study (CS7) used model output to quantify *unmet demand* and *marginal cost variability* under climate-forced scenarios, directly linking meteorological variability to system stress. These quantitative risks were then mapped against social vulnerability indicators (thermal vulnerability, urban heat exposure) to identify where climate-driven power stress is likely to translate into human harm, such as power loss in poorly insulated homes. In CS5, a mismatch between evolving climate drivers and existing risk-management frameworks is observed especially in the Carpathian countries. While both regions may face tourist individual behavioural adaptation gaps, the Carpathians exhibit deeper systemic failures related to fragmented governance, data scarcity, and limited institutional and social capacity for adaptation.

Including socioeconomic impact assessments across the CROSSEU case studies have revealed new information about how promoting sustainable development, equity, and economic effectiveness can be addressed jointly in climate risk and adaptation assessments. It has been demonstrated across the CROSSEU case studies that climate events translate into losses across various human "functionings" (*what humans actually do)* and freedoms in what they want to do. By integrating stakeholder feedback and impact data, the findings identified that the resulting reduction in capabilities is disproportionately experienced by vulnerable groups—such as the elderly, low-income populations, and women facing psychological distress—and this knowledge is crucial for guiding equitable responses. Specifically, the key impact categories consistently identified across hazards—from the ability to maintain good health (heat) and access safe housing (flood) to the ability to enjoy recreational activities (drought and snow)—underscore the universal yet differentially experienced burden of climate change on basic human well-being. This approach is therefore essential not only for prioritizing adaptive investment to protect core capabilities but also for ensuring that future climate-resilient development pathways actively maximize the choices and opportunities of the vulnerable populations in Europe.

4. Conclusion and Recommendations

This report, Deliverable 2.3 (D2.3), titled *"Quantitative and Qualitative Assessments of Societal and Human Aspects of Vulnerabilities,"* represents a critical synthesis of the CROSSEU project's analysis of climate hotspots (CCHs) across Europe. While previous work focused on biophysical and purely economic risks, D2.3 transitions to a human-centered approach, quantifying the often less-monetized societal dimensions of climate vulnerability.

The findings of D2.3 underscore that climate risk in Europe is not merely a function of physical hazards but is deeply mediated by pre-existing social, economic, and institutional conditions. Using Amartya Sen's Capability Approach and Martha Nussbaum's ten central human capabilities as a framework, the report evaluates how extreme climate events—including heat, drought, storms, floods, and snow—restrict fundamental freedoms such as bodily health, mobility, and secure shelter. The integration of the Capability Approach has revealed that the "true burden" of climate change includes non-monetary losses such as psychological trauma, restricted mobility, and the erosion of local cultural spaces.

A critical takeaway is the inequality of adaptive capacity; younger, lower-income, and socially isolated populations (such as the widowed elderly) consistently face higher barriers to self-protection and relocation. Furthermore, the report identifies a governance landscape that is often fragmented and suffers from low visibility, where citizens lack trust in national policies and remain uninformed about post-disaster procedures.

The report concludes that effective adaptation must move beyond infrastructure to include socially targeted strategies, such as building retrofits for low-income households and the expansion of blue-green infrastructure (BGI). To build resilience, European policy should transition from reactive disaster management toward long-term, climate-informed planning that explicitly accounts for demographic shifts—such as population aging—and targets resources toward the most marginalized groups.

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Annexure

CSA1 Annex

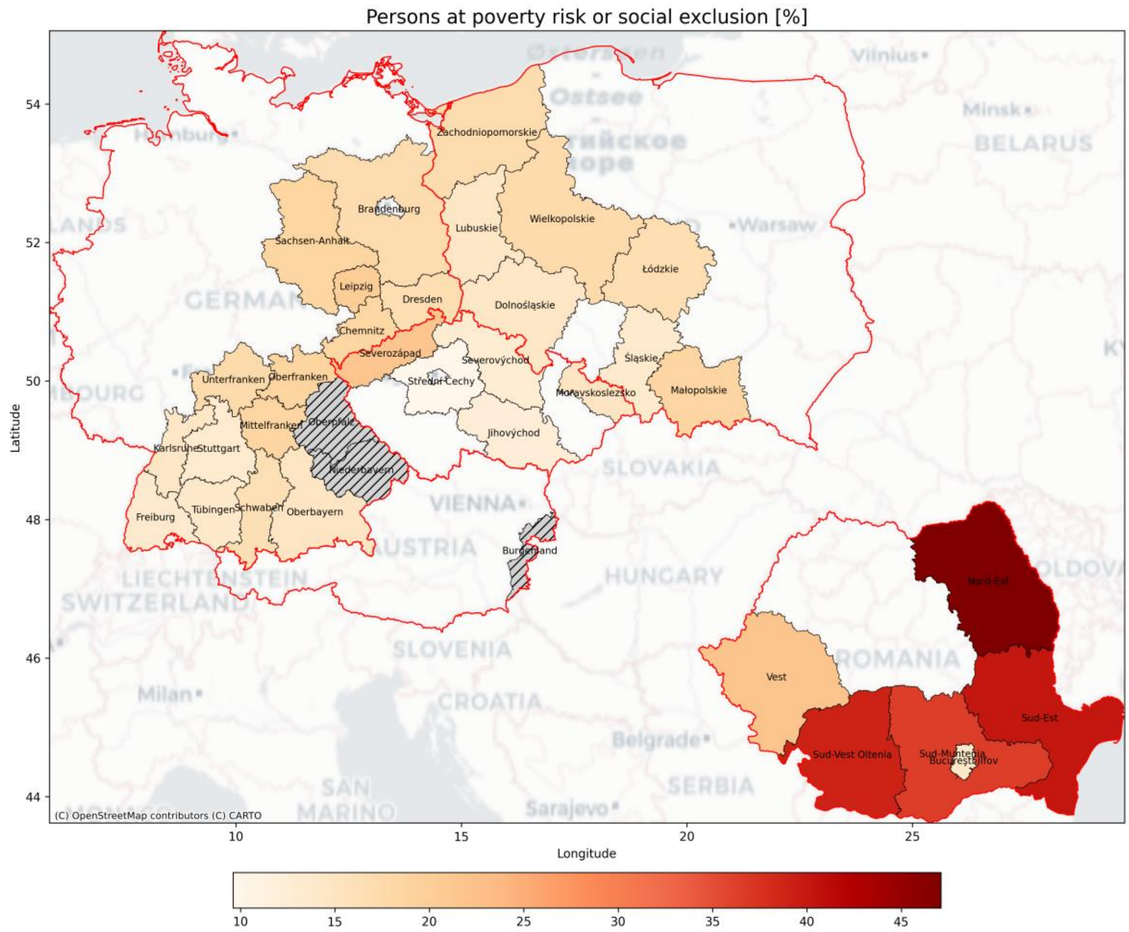
Table1 Capability categories and selected indicators.

Capability	Nussbaum´s categories	Functioning	Wellbeing	Indicator (qualitative/ quantitative) for measuring capabilities*
Being able to maintain good health	Bodily Health	People can stay hydrated, cool, and avoid heat-related illnesses.	Basic needs	• heat-related mortality and morbidity risk
Being able to access cool and safe public spaces	Bodily Integrity	People can visit parks, libraries, or shopping malls to avoid heat stress.	Living conditions	•distance to nearest cooling facility, •capacity of cooling facilities, •number of cooling facilities per capita
Being able to receive timely public information about heat risks	Senses, Imagination, and Thought	People are informed via alerts or education on how to stay safe during heat events.	Living conditions	• level of development of heat-prevention plans - number of HPP components involved - https://doi.org/10.1016/j.envres.2018.11.006 or HPP score in Urban et al. (under review)
Being able to adapt homes to reduce indoor overheating	Control Over One's Environment (Material)	People can insulate their homes, install shading, or improve ventilation.	Living conditions	• indoor heat stress •% of air conditioning in households
Being able to participate in urban greening initiatives	Affiliation	Residents can engage in planting trees or creating green roofs to reduce urban heat.	Living conditions	• number/ km access to community gardens • standards and rules for community gardens
Being able to access clean and sufficient drinking water	Bodily Health	Residents can stay hydrated and avoid dehydration during heatwaves.	Basic needs	• N households without access to fresh water • chemical quality of fresh water during heat waves and the draught
Being able to maintain access to fresh and	Bodily Health	People continue to access markets or	Basic needs	• hygiene standards? • risk of food/water borne diseases incidence

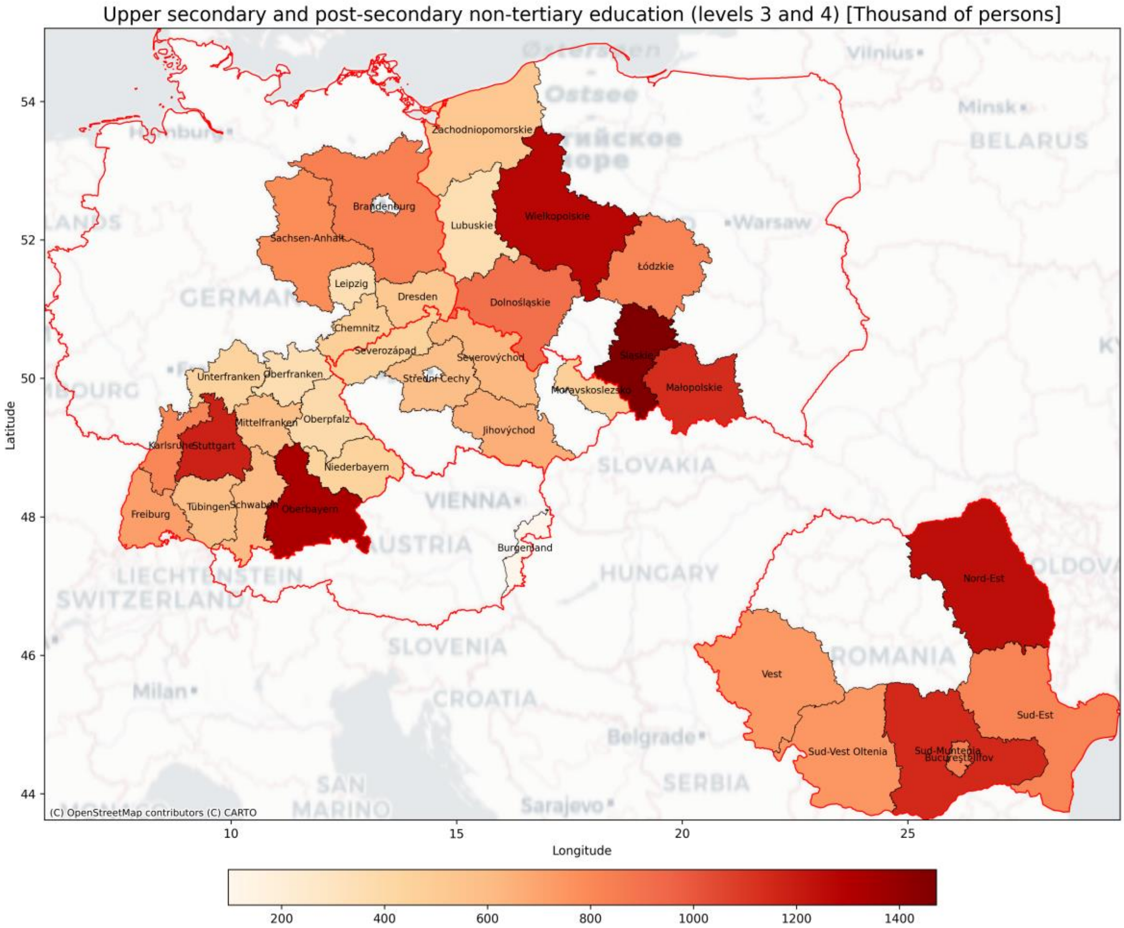
affordable food		stores with perishable food unaffected by heat-related disruptions.		
Being able to safely enjoy public and cultural spaces as a tourist	Play	Tourists can access shaded, ventilated, and cooled areas while exploring the city, ensuring a safe and enjoyable experience.	Living conditions	• N of cooling/points centers in touristic areas • access to fresh water in public toilets and touristic areas in general
Being able to safely spend time outdoors during summer holidays	Bodily Integrity	Children and teens can play, socialize, and move freely without exposure to dangerous heat.	Living conditions	• RR of heat related morbidity (ambulance calls, hospitalizations) for children and adolescent • thermal comfort at playgrounds and areas for sport and free time activities
Being able to access youth programs and spaces adapted for heat safety	Affiliation	Young people can attend summer programs or access recreational spaces that offer shade, cooling, and supervision.	Living conditions	• checking/measuring quality of summer camps (not only) in cities regarding their training for heat related illnesses.
Being able to make informed choices about heat safety through education	Senses, Imagination, and Thought	Teens and children understand heat risks and know how to protect themselves, leading to safer behaviors.	Living conditions	• assessment of high school colloquia in terms of public health education, environmental risks, etc...

CSA2 Annex

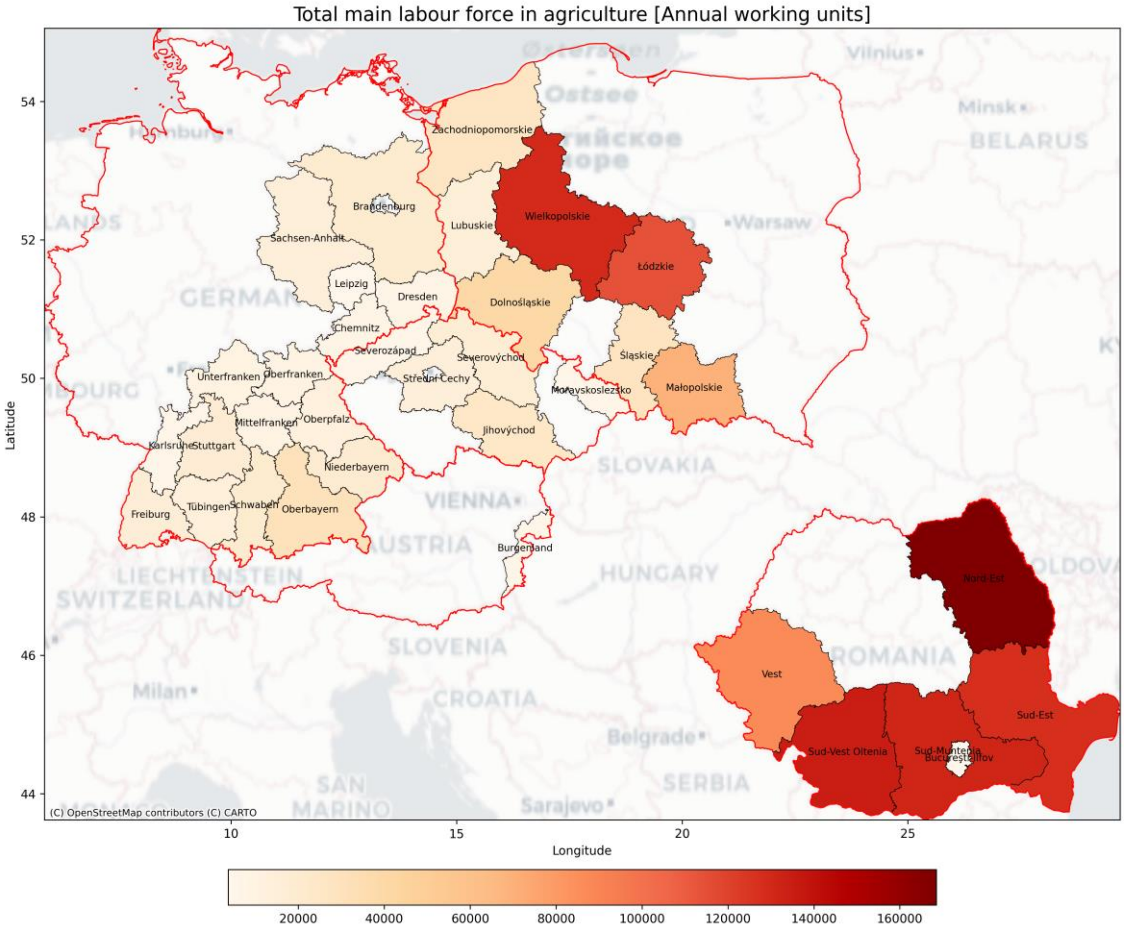
This annex presents additional results on the assessment of social vulnerability in relation to drought, realized within CSA2.



(a)


Upper secondary and post-secondary non-tertiary education (levels 3 and 4) [Thousand of persons]
Latitude
Longitude
Zachodniopomorskie
Brandenburg
Sachsen-Anhalt
Lubuskie
Wielkopolskie
Łódzkie
Leipzig
Dresden
Dolnośląskie
Chemnitz
Severozápad
Severovýchod
Śląskie
Małopolskie
Unterfranken
Oberfranken
Střední Čechy
Moravskoslezsko
Mittelfranken
Oberpfalz
Jihovýchod
Karlsruhe
Stuttgart
Niederbayern
Freiburg
Tübingen
Schwaben
Oberbayern
Burgenland
Nord-Est
Vest
Sud-Est
Sud-Vest Oltenia
Sud-Muntenia
Bucureşti-Ilfov
(C) OpenStreetMap contributors (C) CARTO
200
400
600
800
1000
1200
1400

(b)


Total main labour force in agriculture [Annual working units]
Latitude
Longitude
Zachodniopomorskie
Wielkopolskie
Łódzkie
Lubuskie
Brandenburg
Sachsen-Anhalt
Leipzig
Dresden
Dolnośląskie
Chemnitz
Severozápad
Severovýchod
Střední Čechy
Śląskie
Małopolskie
Moravskoslezsko
Unterfranken
Oberfranken
Mittelfranken
Oberpfalz
Jihovýchod
Karlsruhe
Stuttgart
Niederbayern
Freiburg
Tübingen
Schwaben
Oberbayern
Burgenland
Nord-Est
Vest
Sud-Est
Sud-Vest Oltenia
Sud-Muntenia
Bucureşti-Ilfov
(C) OpenStreetMap contributors (C) CARTO
20000
40000
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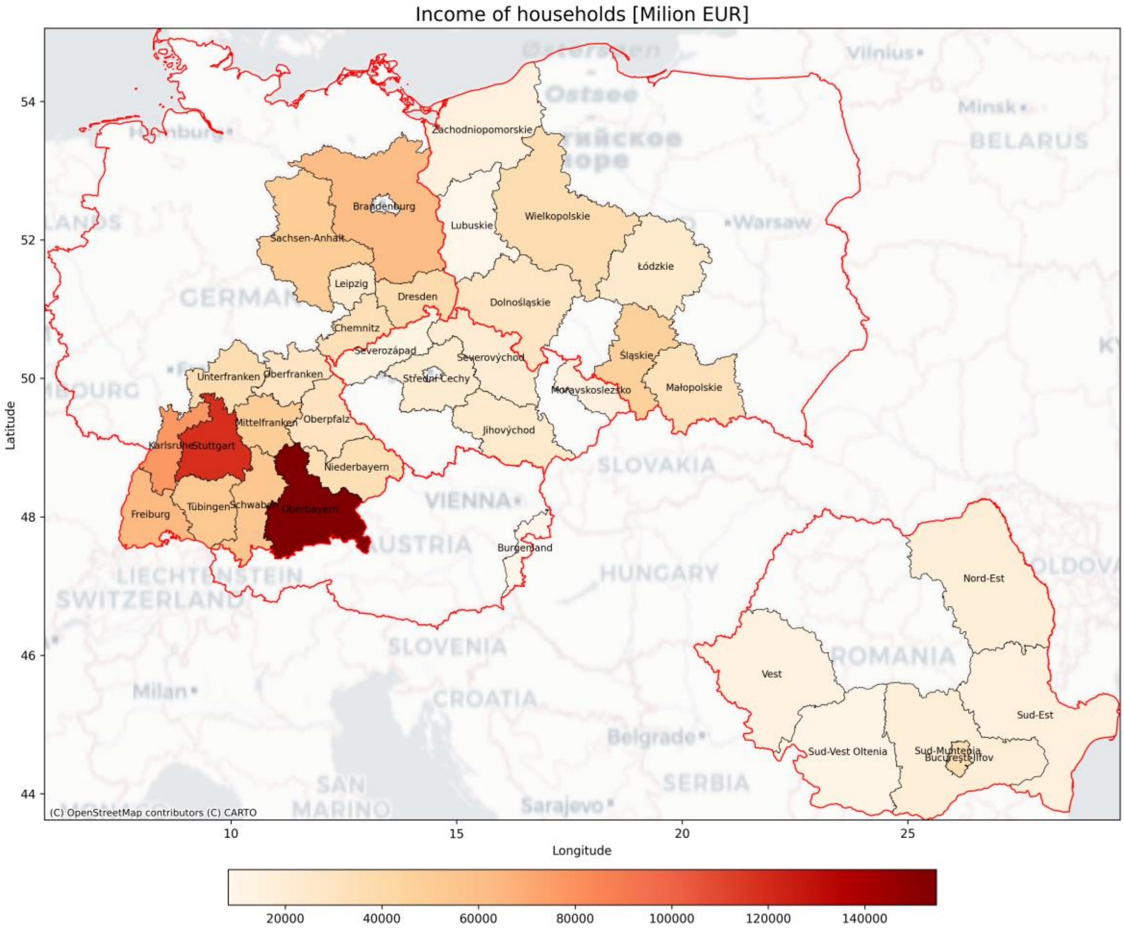
80000
100000
120000
140000
160000

(c)



(d)

CSA2-AnnexFigure1. Quantitative indicators used for the assessment of social vulnerability to drought at NUTS2 level, based on data available from EUROSTAT: (a) population at risk of poverty or social exclusion, for year 2019, expressed as percent from total (NUTS2) population; (b) Population in private households, age class from 15 to 64 years, with upper secondary and post-secondary non-tertiary education (levels 3 and 4) for year 2024; (c) total main labour force in agriculture, for year 2023; (c) income of households, data for year 2022; (d) income of households by NUTS2 region, for 2022.

CSA3 Annex

CSA3_AnnexTable1 Capability categories and selected indicators.

Capability	Nussbaum´s categories	Functioning	Relevance	Influenceability	Indicator (qualitative/ quantitative) for measuring capabilities*
Being sheltered	Bodily health, Life	Safety and security	Damage to homes/shelter	Relocation assistance, flood shelters	• Number of homes damaged* • Damage cost of houses* • Days spend on household restoration¤
Being able to meet physiological needs and being mentally healthy	Bodily health, Life	Healthy	Physical injuries, infections, water-borne diseases, stress and trauma.	Accessible healthcare for vulnerable groups, mental health support programs,	• Number of persons/households with flood-related physical health issues or injuries¤
Being able to access energy services	Life	Reliable access to energy	Disruption in critical utility infrastructure, power outages	Flood-proofing critical energy infrastructure, promotion of renewable energy sources	• Number of households without access to electricity during and post-flood
Being able to sustain livelihoods and economic activities	Bodily Integrity	Mobile	Disruption in infrastructure	Flood-proofing infrastructure	• Change in commute time due to flood damaging roads* • Increased commute time due to rehousing post-flood¤
Being able to be educated/ having the opportunity to get education	Senses, Imagination, and Though	Educated	Damage to transport infrastructure	Investment in resilient transport infrastructure	• Duration of educational institution closure due to damage caused by flooding
Being able to have job security	Life Control Over One's Environment_ Material	Secured job	Damage to schools, disruption in transport	Investment in safe infrastructure	• Damage to industrial buildings*
Being able to connect socially	Senses, Imagination, and Though Emotions	Socially connected	Absences from work, business closure	Promoting flood-resilient industries, job placement services	• Number of social venues/summer houses damaged/inaccessible*
Being able to be nourished	Bodily health, Life	Nourishment	Disruption of food supply chains	Delivery of food and water aid, community-based food storage programs,	• Number of grocery stores / essential food retailers closed in the area post-flood • Duration of piped water supply cut

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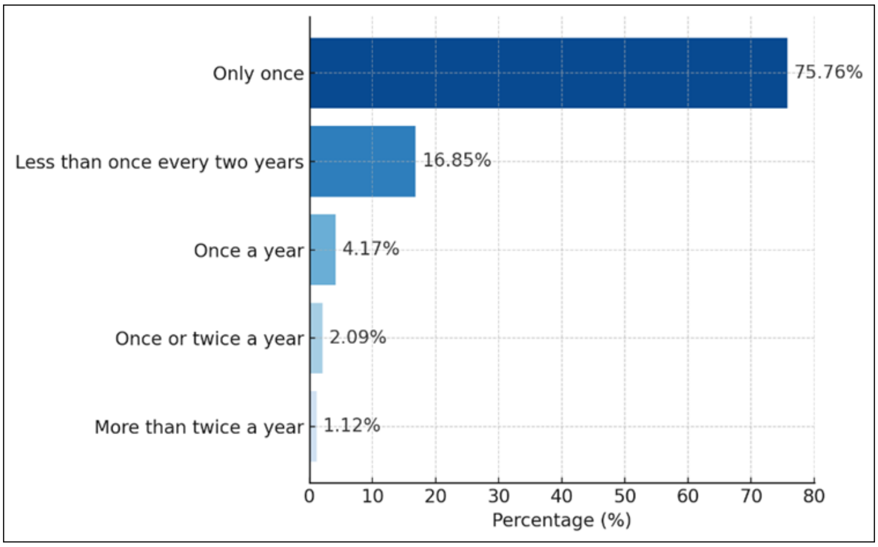
CSA4 Annex

This annex presents additional results from the survey conducted as part of the CSA4, aimed at assessing behavioural, perceptual, and institutional dimensions of local resilience to flood risk. These results complement the main findings reported in Section 2.4.

Previous experience and risk expectations

The survey explored respondents' direct experience with flood events. Overall, 31% of respondents (n = 623) reported having personally experienced at least one flood event in their lifetime. Among these, nearly 76% stated they had been affected only once in the past years, while 17% reported experiencing flooding less than once every two years (Annex Figure 1).



CSA4_AnnexFigure1: Previous flood experience.

In terms of severity, respondents with prior experience were also asked to indicate the duration of the worst flood they had experienced (Annex Figure 2). Approximately 44% reported an event lasting 2–3 days, while 35% had experienced floods lasting one day only.

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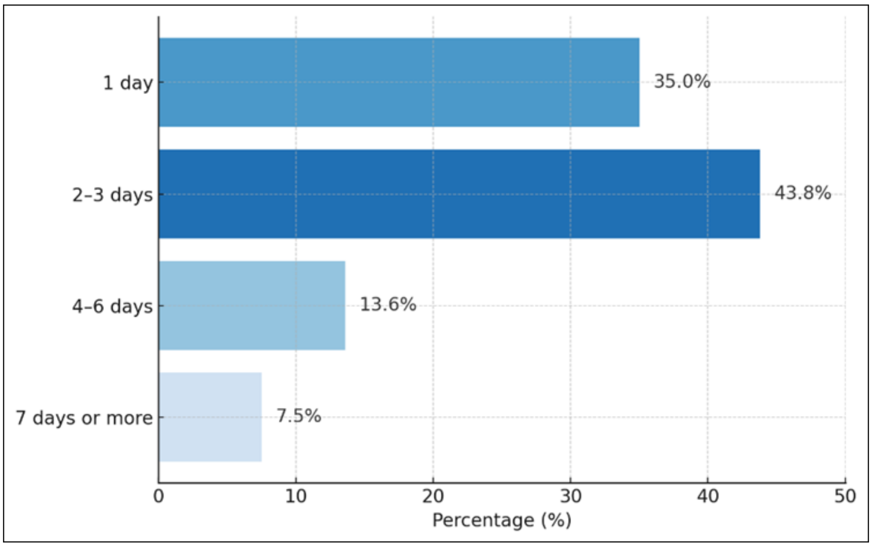
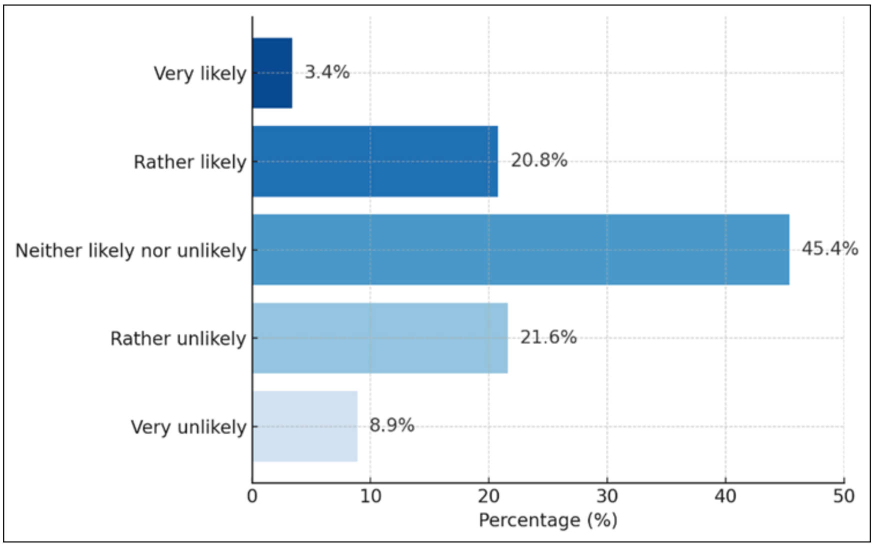


CSA4_AnnexFigure2: Duration of the worst flood event.

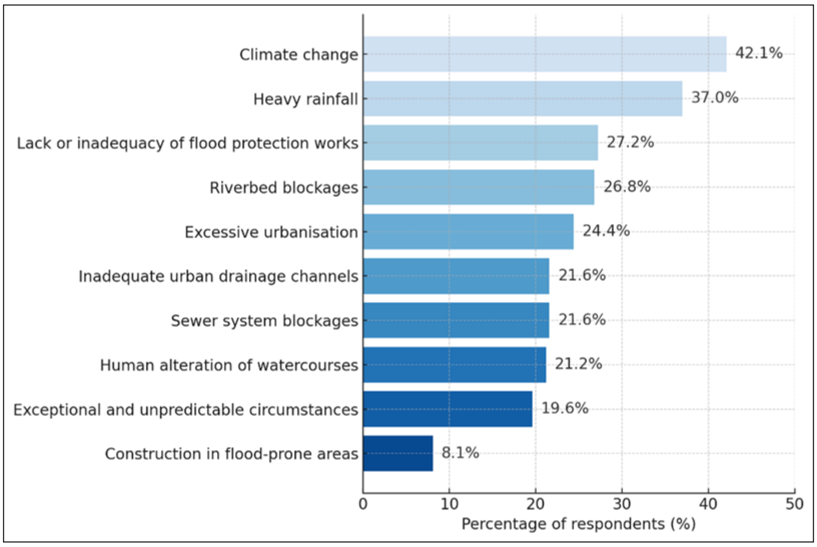
The survey included a further item asking respondents to estimate the probability that their municipality would be affected by a flood in the next five years. This question captures individual expectations of near-term flood risk at the local level, providing insight into how people internalise and anticipate climate-related hazards. Results are reported in Annex Figure 3. Notably, nearly one in four respondents (24.2%) consider it rather or very likely that their municipality will experience a flood within the next five years. This reflects a non-negligible level of risk salience, suggesting that a significant portion of the population perceives flood threats as both plausible and immediate. The largest group (45.4%) selected the midpoint of the scale, indicating uncertainty or ambivalence about the likelihood of future floods.



CSA4_AnnexFigure3. Perceived probability of flooding over the next five years.

Public beliefs about the causes of flooding

To better understand how local residents interpret the drivers of flood events, the survey included a multiple-choice item asking respondents to identify up to three main causes of flooding in their province. The question aimed to capture prevalent narratives and attribution patterns that may shape attitudes toward mitigation responsibilities and support for adaptation policies. As shown in Annex Figure 4, the most frequently cited cause was climate change, followed by heavy rainfall. At the same time, several causes linked to infrastructure and land management were also frequently selected, including the lack of or inadequacy of flood protection works, riverbed blockages, and excessive urbanisation. Interestingly, only 8.1% mentioned construction in flood-prone areas, suggesting a potential underestimation of individual and collective land-use choices in shaping local vulnerability. These results indicate a dual perception, in which both natural-climatic factors and human-induced vulnerabilities are recognised as contributing to flood risk.



CSA4_AnnexFigure4: Perceived causes of flood risk.

Ecosystem aspects in results

Some survey responses suggest that ecosystem-related factors are taken into account by a portion of the population when evaluating flood risk, its causes and possible solutions. These aspects go beyond the physical presence of natural elements and concern how individuals interpret the role of ecological functions and environmental degradation in shaping both flood drivers and the effectiveness of M&As.

An initial indication emerges from the question on the perceived causes of flooding, results are reported in CSA2 Annex Figure 4. In addition to climatic factors, many respondents recognised human-induced pressures, especially riverbed alteration and excessive urbanisation, as drivers of flood risk, reflecting awareness of how disrupted land use and hydrological systems contribute to local vulnerability. These responses indicate a dual understanding of risk causation, in which natural hazards are compounded by the degradation of regulating ecosystem services, such as water retention and soil infiltration. This interpretation assigns responsibility not only to extreme weather or insufficient infrastructure, but also to structural failures in land and environmental management, consistent with findings in the literature on flood risk perception (Wachinger et al., 2013; Ferreira et al., 2022; Anderson et al., 2021).

The salience of ecosystem-based reasoning is supported by responses concerning the perceived safety of different flood protection measures (Figure 1). Among the four interventions assessed, two, i.e. watershed restoration and infiltration trenches, clearly fall within the domain of NBS. Watershed restoration emerged as one of the most positively perceived options, suggesting public confidence in large-scale, ecologically grounded strategies. In contrast, infiltration trenches received more sceptical evaluations, possibly due to their lower visibility and perceived technical unfamiliarity. As noted in previous studies, support for NBS depends not only on perceived effectiveness but also on their alignment with local values, such as landscape identity and local heritage, which tend to resonate strongly with citizens (Sarabi et al., 2019; Anderson et al., 2021). Communicating NBS benefits through place-based narratives and participatory demonstration may therefore be essential to enhance their social acceptability (Han and Luo, 2024).

Perceptions of green infrastructure investment appear more divided (Figure 2). While a relevant share of respondents express support for measures such as parks and wetlands, overall agreement remains limited, and a substantial portion expresses uncertainty or disagreement. These findings suggest that public support for ecosystem-based adaptation is still partial and not fully consolidated. On the other hand, insights from the stakeholders' perspective (see section 2.4.4) show greater convergence, identifying river renaturation and ecosystem restoration as priority measures for addressing both hydrological and ecological vulnerabilities. In this context, NBS are more firmly embedded in institutional discourses than in public perceptions, indicating the need for targeted engagement strategies to strengthen the social basis for their implementation.

Capabilities Impacted

CSA4_AnnexTable1: Capability categories and selected indicators.

Capability	Nussbaum´s categories	Functioning	Wellbeing	Relevance	Influenceability	Indicator (qualitative/ quantitative) for measuring capabilities*
Being able to move freely and access essential services	Bodily Integrity	Mobile	Basic needs	road closures and landslides in mountain areas, disrupted mobility and isolated communities	Improve flood-resilient road infrastructure; early warning systems; emergency transport plans	% of road network flooded; % of residents reporting damage to vehicles
Being safe	Life	Safety	Basic needs	reduced exposure and improved safety conditions	investments in M&As	Societal willingness to pay for flood mitigation and adaptation measures; % of respondents who have experienced flood; Individual perceived safety of M&As
Being able to live in safe housing	Bodily Health	Safety	Basic needs	Flooding of residential areas compromises physical safety, causes displacement and damages personal belongings	Flood-resilient urban planning; relocation incentives; retrofitting housing;	% of flooded residential areas; % of residents that experienced damage to their home during flood events; % of residents reporting damage to personal belongings; % of residents who express willingness to relocate due to flood risk

Being able to preserve one's physical and mental health	Bodily Health	Safety	Basic needs	injuries, illness due to exposure or poor sanitary conditions, and significant psychological stress	improved access to emergency and mental health services	% of residents reporting flood-related physical health issues; % of residents reporting flood-related psychological stress
Being able to work under safe and stable conditions	Control over one's environment (Material)	Secured/continuous access to job	Living conditions	work interruptions due to damage, infrastructure failure, and inaccessibility	Emergency income support, worker protection schemes	% of residents reporting work interruption due to flooding
Being able to maintain work opportunities and income	Control over one's environment (Material)	Accessing and carrying out work, farming, or running a business	Living conditions	damage productive infrastructures, reduce access to workplaces, destroy crops, and interrupt tourism services	Structural and nature-based flood protection; business continuity support; insurance schemes; adaptation incentives for agriculture and tourism	% of flooded productive areas % of flooded agricultural land % of flooded tourism infrastructure
Being able to rely on trustworthy institutions	Control over one's environment (Political)	Feeling protected and supported by institutions	Living conditions	Low trust undermines individuals' perception of safety and reduces willingness to follow warnings, adopt protection measures, or contribute financially	Improve institutional transparency; strengthen communication; participatory planning	citizens degree of trust in local institutions to manage flood risk

Gender and social inclusion Dimensions

CSA4_AnnexTable2: Incidence of flood damage by sociodemographic characteristics.

Type of damage experienced	Gender (%)			Age class (%)			Income*(%)			
	Male	Female	p-value	18-64	≥65	p-value	Low	Medium	High	p-value
Damage to the home (e.g. roof, walls, windows)	31.58	28.67	0.429	30.68	29.98	0.863	26.85	33.82	24.05	0.140
Damage to personal belongings (e.g. furniture, appliances, valuables)	27.24	27.67	0.906	25.57	28.19	0.509	29.63	30.64	20.25	0.182
Damage to personal vehicles	22.91	18.67	0.193	18.18	21.92	0.301	18.52	19.94	18.99	0.941
Damage to agricultural or forest property (e.g. garden, trees, smallholding)	17.96	22.33	0.173	11.93	23.27	0.001	17.59	21.1	22.78	0.644
Work interruption or loss of income	20.43	19.00	0.653	18.18	20.36	0.539	19.44	21.1	18.99	0.878
Health problems (e.g. injury or flood-related illness)	2.17	2.33	0.889	0.57	2.91	0.076	1.85	2.31	2.53	0.945
Psychological stress	31.89	43.00	0.004	38.07	36.91	0.788	38.89	39.88	30.38	0.289
No damage reported	30.65	22.33	0.019	34.66	23.49	0.005	36.11	19.65	35.44	<0.001

Notes. P-values are based on Pearson's chi-square tests conducted on the full binary distribution of responses (i.e. whether or not the respondent reported each type of damage). For brevity, only the proportion of affirmative responses is reported. Respondents could indicate more than one type of damage. *Income classes are self-reported: low (up to €19,999), medium (€20,000–49,999), and high (€50,000 or more).

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CSA4_AnnexTable3: Perceived ability and willingness to relocate by sociodemographic characteristics.

	Gender (mean score)			Age class (mean score)			Income* (mean score)			
	Male	Female	p-value	18-64	≥65	p-value	Low	Medium	High	p-value
I have no choice about where I live	3.10	3.06	0.388	3.28	3.01	<0.001	3.26	3.10	2.78	<0.001
I am willing to relocate to an area with lower flood risk	2.85	2.81	0.448	2.78	2.84	0.263	2.92	2.83	2.71	0.071
I prefer to live here despite flood exposure because there are advantages for me	3.28	3.21	0.118	3.32	3.22	0.041	3.22	3.28	3.31	0.464
I do not have the resources or capacity to protect myself from flood exposure	3.28	3.27	0.856	3.36	3.25	0.029	3.41	3.29	3.08	<0.001

Notes. Mean scores are based on a five-point Likert scale assessment ranging from 1 (strongly disagree) to 5 (strongly agree). *P*-values refer to one-way ANOVA tests conducted for each item across the sociodemographic groups. Higher values indicate greater agreement with each statement. *Income classes are self-reported: low (up to €19,999), medium (€20,000–49,999), and high (€50,000 or more).

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