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D2.1- Assessment Methodology for CCHs and STLs

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Author(s)	DTU: Kirsten Halsnæs, Shreya Some MeteoRo: Sorin Cheval, Dana Micu, Vladut Falcescu, Argentina Nertan UNIPD: Mara Thiene, Cristiano Franceschinis, Marco Borga K&I: Gabriele Quinti UB: Denisa Igescu, Relu Giucă, Mihai Adamescu, Georgia Arhire CZU: Aleš Urban UEA: Katie Jenkins UCL: Alvaro Calzadilla, Olivier Dessens WEMC: Kristian Nielsen EDF: Boutheina Oueslati, Sandrine Charousset
Reviewed by	DTU: Per Skougaard Kaspersen

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	MeteoRo: Sorin Cheval, Vlad Amihaesei, Monica Paraschiv, Angela Cristina Plescan, Laurentiu Ciuhu HEREON: Paul Bowyer BOKU: Alice Ludvig, Katharina de Melo CZU: Laura Míčková LGI: Anne-Charlotte Costabadie
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Executive Summary

This deliverable (D2.1) outlines a harmonised methodology for assessing socio-economic risks and impacts of climate change within case study areas, defined as Climate Change Hotspots (CCHs) and explored through Storylines (STLs). The framework was developed within Work Package 2 of the CROSSEU project and draws on existing EU projects and best practices to ensure consistency and facilitate upscaling to broader European contexts. It emphasises stakeholder engagement and a six-step approach encompassing scenario development, data integration, impact and risk assessment, adaptation options, and decision support tools. Finally, the framework provides a crucial foundation for the CROSSEU Decision Support System (DSS). It provides the workflows for the construction of the on-line DSS, and the requirements needed to present the range of outcomes to stakeholders in an easy-to-use interface, empowering them to make informed decisions for managing climate-related risks.

Keywords

Capability Approach, Climate Change, Climate Change Hotspots, Climate Resilience, Climate Adaptation and Mitigation, Cross-sectoral, Climate Change Impact, Consequences, Event-based Storylines, Methodology, Socio-economic Impacts and Risks, Vulnerability

Abbreviations and acronyms

Acronym	Description
AINEVA	Association of Regions and Autonomous Provinces of the Italian Alpine Arc
ARPAV	Regional Agency for Prevention and Environmental Protection of Veneto (Italy)
CBA	Cost-Benefit Analysis
CCHs	Climate Change Hotspots
CEA	Cost Effective Analysis
CELVA	Consortium of Local Authorities of the Aosta Valley (Italy)
CROSSEU	Cross-sectoral Framework for Socio-Economic Resilience to Climate Change and Extreme Events in Europe
DSS	Decision Support System

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EIA	Environmental Impact Assessment
EGD	European Green Deal
ESPON	European Observation Network for Territorial Development and Cohesion
EU	European Union
IPCC	Intergovernmental Panel on Climate Change
IRIs	Integrated Risk Indicators
MCA	Multicriteria Analysis
NUTS	Nomenclature of Territorial Units for Statistics
RCP	Representative Concentration Pathways
PN-NMA	Nivometeorological Programme of the National Meteorological Administration (Romania)
SRA	Social Risk Analysis
SSP	Shared Socioeconomic Pathways
STL	Storylines
SDGs	Sustainable Development goals
WP	Work Package

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1. Introduction

Work Package 2 (WP2) of CROSSEU focuses on the development of harmonized methodologies for evaluating socio-economic risks and impacts in case study areas. This deliverable, D2.1, presents the methodological framework for co-producing integrated assessments of these risks. The framework is based on an initial review and further development of similar applications and harmonization protocols in other relevant EU projects.

The European Green Deal (EGD) sets an ambitious target for the European Union to become a climate-neutral and resource-efficient economy by 2050. Achieving this requires a deep understanding of the socio-economic risks and opportunities arising from climate change and extreme weather events. The CROSSEU project, funded by Horizon Europe, seeks to address this need by developing a cross-sectoral framework for assessing and managing these risks. A key aspect of this is understanding the impacts within specific geographical areas and socioeconomic sectors, defined within CROSSEU as Climate Change Hotspots (CCHs) and using Storylines (STLs).

Overview of Climate Change Hotspots (CCHs) and Storylines (STLs)

Climate Change Hotspots (CCHHs) represent specific geographical areas experiencing significant climate change impacts. Storylines (STLs) are narratives of plausible future events that combine projected climate change trends with socio-economic developments. These STLs help to explore the potential consequences of climate change within the CCHs in a tangible and relatable way. Evaluating the socio-economic risks and impacts within CCHs and through the lens of STLs is crucial for understanding the multifaceted consequences of climate change. This includes identifying vulnerable sectors, populations, and regions, and ultimately informing effective adaptation and mitigation strategies.

Purpose of the Deliverable

Deliverable D2.1 was developed in Work Package 2 (WP2) of the CROSSEU project, which aims to develop a harmonized methodology for assessing socio-economic risks and impacts, which can be related to case studies with specific geographical areas and a basis for upscaling to larger European areas. The report presents a co-produced framework for integrated assessments of these risks, drawing upon existing knowledge and best practices from other EU projects like COACCH, PESETAS and IMPACT2C.

The framework developed in WP2 T2.1 is designed to be participatory, involving stakeholders in the joint identification of sectoral gaps, needs, and priorities for coping with socio-economic impacts of climate change.

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This participatory approach is essential for ensuring that the assessments are relevant and applicable to the needs of different sectors and regions.

Objectives of Developing a Harmonised Methodological Framework for assessing socioeconomic impacts in case study areas for CCHs and STLs

The primary objective is to establish a consistent and robust methodology for assessing socio-economic risks across different CCHs and STLs. This facilitates comparability- and upscaling of the findings to broader European contexts. The harmonized approach also promotes collaboration and knowledge sharing among stakeholders.

Structure of the Deliverable

This deliverable is structured to provide a clear and comprehensive overview of the developed methodology and its application.

Outline of the Key Sections and Content Covered in the Deliverable

- Methodological Framework: Six-Step Approach (Section 2): Details the step-by-step process for conducting integrated assessments, encompassing climate and socio-economic scenarios, spatial data integration, impact and risk assessment, adaptation options, and decision support tools.
- Integrated Analysis of SE Risks and Impacts (Section 3): Explores the core data and methodologies used in the analysis, including decision-making perspectives, damage cost assessments, social and human dimension considerations, and relevant tools like Cost-Benefit Analysis (CBA) and Multi-criteria Assessment.
- Case Study Elaboration (Section 4): Demonstrates how the framework is applied in various case studies across different CCHs and STLs, showcasing its practical implementation.
- Cross-Cutting Consistency and Comparison for Upscaling (Section 5): Discusses how findings from individual case studies can be compared and synthesized to draw broader conclusions and inform upscaling efforts.

This framework provides a crucial foundation for the CROSSEU project, enabling a systematic and rigorous assessment of socio-economic risks and impacts. The insights generated will be used to develop the CROSSEU Decision Support System (DSS), empowering stakeholders to make informed decisions and actionable insights for managing climate-related risks.

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2. Methodology Framework: Six-Step Approach

The aim of the methodology framework is to facilitate comparability and consistency across case studies and other components of CROSSEU. CROSSEU includes a range of modelling and qualitative studies aimed at assessing the risks of climate extremes within WP1 and WP2.

The assessment of STLs in all eight case study areas is structured around common analytical steps illustrated in the figure below, which is used as an analytical structure in WP2 (Figure 1)

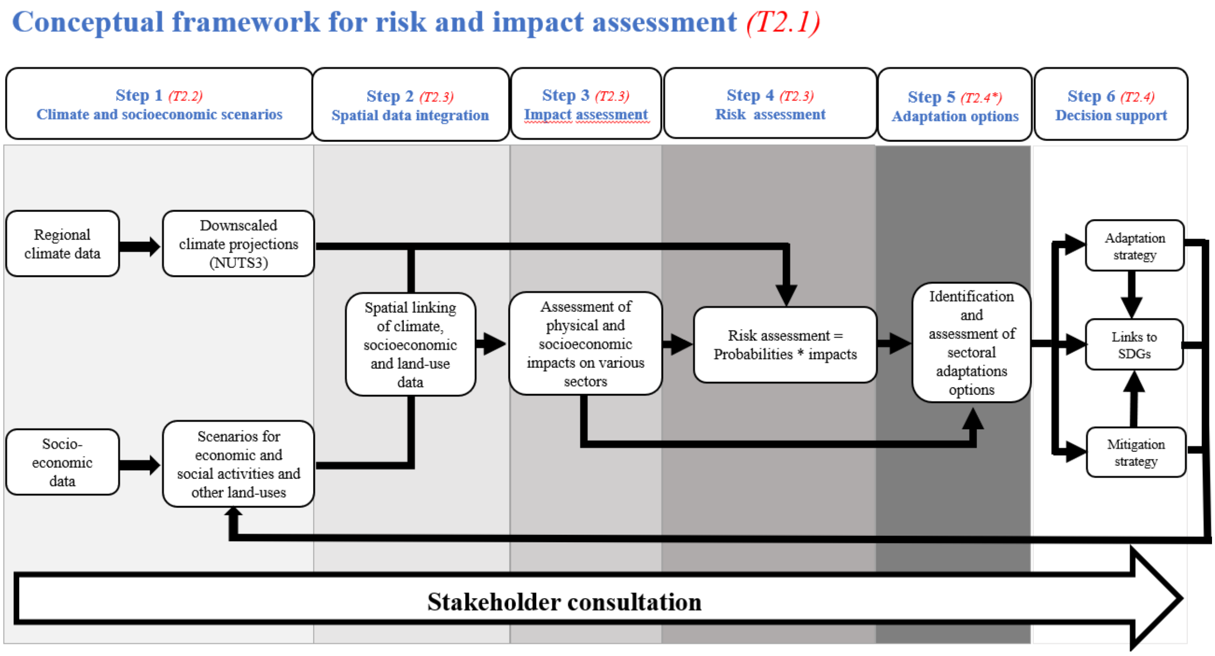

Figure 1: Methodology framework for risk and impact assessment

2.1 Step 1: Climate and Socioeconomic Scenarios

In this step, socio-economic scenarios are created for each Storylines (STL) case study. Typically, there will be two classes of scenarios:

- climate change scenario (where additional forcing from a changing climate is considered) in relation to the climate change hotspots (CCHs)
- Socioeconomic scenarios
- projecting trend without climate change

In reference and climate scenarios *at least* two dimensions will be considered: the physical climatic projections and the socioeconomic projections. Physical parameters (e.g., temperature and precipitation) will be predicted using climate models or earth system models. All case studies will use the same climate scenarios including a mean value for RCP8.5 and a mean value for RCP4.5. Case studies can supplement with other scenarios for sensitivity analysis if wanted. Typically, output from coarse resolution (global or regional) climate models are downscaled to a finer spatial

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resolution to provide more accurate data of importance to the assessment of socioeconomic impacts of climate change hazards. In CROSSEU, we use a range of different climate scenarios with output obtained from global and regional (including convection permitting scale) climate models.'

This can be one of the challenging aspects of this step, and the distribution of local climate parameters (such as precipitation) is potentially highly uncertain.

The socioeconomic scenarios describe future socioeconomic activities in the CCH. It can be difficult to develop socioeconomic scenarios at a very detailed case study level, in particular in relation to case study areas, which are using very detailed data with a high geographical resolution e.g. data about land use assets including buildings, cities, people, ecosystems, and economic sectors. A common approach in many studies is to avoid such problems by assuming that the socioeconomic characteristics of an area will be unchanged in the future. Sensitivity analysis can then be used to explore what could happen in terms of climate risks, for example due to further urbanization or the population ageing. The socioeconomic scenarios should have important assumptions noted in the projections and can also include estimates for the uncertainty bounds for historic data and projected scenarios.

The climate change scenario will be based on outputs from climate models or earth system models. Depending on the time frame considered (2030, 2050, 2100), climate change projections will be strongly conditioned on different emission scenarios as mentioned above.

2.2. Step 2: Spatial Data Integration

In this step, a geographical representation of the socio-economic activities and land use will be developed, which can be linked to the downscaled climate information for the hotspots. To do this, it is necessary to clearly define the geographic boundaries of the case studies and in this context also consider the governance boundaries, which are relevant to decision making issues. For example, in a Danish context, relevant governance boundaries are municipalities, regions or national level. If possible NUTS3 level data is to be used. The spatial data integration can for example be modelled using a Geographical Information System.

2.3 Step 3: Impact Assessment

Downscaled data from regional climate models, coupled with socioeconomic scenarios can be used as input to impact models (e.g., flood models) to assess physical and socio-economic impacts on various sectors and geographical locations for each case study. The output of this process is a list of physical and socioeconomic impacts, their severity, and the likelihood of occurrence. The measure of the impact can be in monetary or non-monetary terms and both quantitative and qualitative measures can be applied. This opens possibilities for many different types of metrics and

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indicators to measure impacts. The impacts can be measured by different analytical approaches including Cost Benefit Analysis (CBA), a cost effectiveness analysis (CEA), and a Multicriteria analysis (MCA). A short description of these approaches is given below. Also see section 3.2.4 for elaborate explanation.

Cost benefit analysis

The basic idea is to measure all negative and positive project impacts in the form of monetary costs and benefits. Market prices are used as the basic valuation as long as markets can be assumed to reflect "real" resource scarcities. It is in other cases recommended using shadow prices. Shadow prices are meant to reflect prices that would occur in a "perfect" market.

Cost effectiveness analysis

A special sort of cost benefit analysis where all costs of a portfolio of projects are assessed in relation to a policy goal. The policy goal in this case represents the benefits of the projects and all other impacts are measured as positive or negative costs (negative costs, with the exception of the benefits of the policy goal, will correspond to benefits of the policy). The policy goal can for example be a specified goal of risk reduction by adaptation. The result of the analysis can then be expressed as the investment costs of adaptation for a reduction of the number of people affected by a climate hazard.

Multicriteria analysis

The basic idea of the multicriteria analysis is to define a framework for integrating different decision parameters and values in a quantitative analysis without assigning monetary values to all parameters. Examples of parameters that can be controversial and very difficult to measure in monetary values are human health impacts, equity, and irreversible environmental damages.

Therefore, a common guideline for reporting these impacts metrics and indicators will be developed.

2.4 Step 4: Risk Assessment

Climate risk, defined as the probability of the occurrence of extreme events multiplied by the impact of that event, is an important measure to support decisions on appropriate adaptation measures. In general, economic terms, it is beneficial to invest in adaptation measures as the adaptation costs is lower than the expected reduction in damages from climate change achieved by the adaptation. The probability is the likelihood of an event happening at a given point in time. The probability of climate events, e.g. extreme precipitation, will become increasingly likely. Therefore, probabilities of events are time dependent.

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2.5 Step 5: Adaptation Options

The next step is to identify the adaptation options based on the impact and risk assessment. The selection of adaptation options will reflect where there is a large potential gain in reducing the risk of climate events by adaptation in addition to priorities of stakeholders and decision makers. In addition to the direct benefits of adaptation due to risk reduction, the adaptation options can also have synergies and tradeoffs with mitigation and development related goals in terms of Sustainable Development goals (SDGs) or local development targets, which initially can be mapped for the adaptation options. Assumptions made in this stage should be noted in detail to compare across all identified adaptation options in each of the case studies. Furthermore, the analysis of synergies and trade-offs for adaptation options and SDGs will contribute to the T4.3 (dealing with societal impact of adaptation policies and related to social justice, including gender, and considering multiple forms of discrimination or inequality, social cohesion and social exclusion. Also, the analysis will help in documenting how policies can increase the capacity of different groups to adapt to climate risks).

2.6 Step 6: Decision Support

In this step, based on the identified adaptation options, adaptation strategies and related mitigation strategies will be identified for each case study. The monetary impacts and other quantitative or qualitative impacts of the adaptation strategies and as far as possible also to mitigation strategies and SDGs should be included.

In the further development of the common CROSSEU structure for each modelling effort and case we have shown how the different steps will be conducted (Section 4).

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3. Integrated Analysis of Socioeconomic Risks and Impacts: Data and Methodologies

3.1. Decision making Perspectives on Impact and Adaptation Assessments

Decision-making perspectives on impact and adaptation assessments are crucial for guiding informed options in response to the socio-economic risks of climate change. These assessments provide valuable insights into potential risks, vulnerabilities, and adaptation options, considering the uncertainties inherent in climate and socio-economic projections. In this context, the CROSSEU project integrates climate change and socio-economic considerations into the broader development of climate action policy, while engaging a wide range of relevant sectoral stakeholders from climate-sensitive case study areas exposed to four key hazard categories (heat, drought, storm, snow) to co-develop effective strategies for building climate resilient societies.

Informed decision-making is crucial for effective climate risk management and resilience building under the current and future climate change management challenges. By conducting thorough assessments of climate risks, vulnerabilities, and adaptation options, the CROSSEU project supports decision-makers in making informed choices that could prioritize the most effective and sustainable strategies. The project emphasizes the importance of informed decision-making based on scientific knowledge and local insights. For this purpose, CROSSEU acknowledges the role of uncertainty in science-based knowledge and relies on state-of-the-art climate projections and scenarios (RCPs-SSPs) and climate hazard-specific impact assessments at the NUTS3 level in representative case study areas across Europe to address the socio-economic risks of climate change. The project fosters a comprehensive understanding of climate change impacts and adaptation options in relevant STL-CCH areas, supporting informed decision-making at multiple scales. The co-development of a decision-support solution is intended to integrate a range of priorities and perspectives of decision makers in research-based knowledge in all climate-sensitive sectors addressed through the CROSSEU case studies. In support of informed decision-making, CROSSEU: (i) contributes to the understanding of climate change risks, (ii) identifies vulnerabilities, (ii) evaluates adaptation options, (iv) considers how the adaptation efforts aim (also) at equity and social justice, (v) incorporates uncertainty, and (vi) engages stakeholders.

Engaging various stakeholders, such as government bodies (at various levels), local authorities, the private sector, and civil society, bringing together different perspectives and expertise is a key action in the CROSSEU project. Transparent and effective communication of the

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scientific evidence related to climate risks, scenarios, and vulnerability assessments is crucial, allowing the decision-makers to choose effective socially equitable strategies in accordance with their political priorities (Pidgeon and Fischhoff 2011). Furthermore, integrating adaptative actions and management practices into sectoral strategies ensures the flexibility of the policy framework while the cross-sectoral approaches lead to better coordination in climate risk reduction (Biesbroek 2021). By promoting cross-sectoral coordination and incorporating climate change considerations into sectoral policies, the CROSSEU project aims to strengthen the resilience of European societies to climate change impacts facilitating the uptake of actionable science-based knowledge for informed decision-making (the CROSSEU DSS).

Decision-making under uncertainty poses significant challenges when addressing climate risks that involve variable climate projections and evolving socio-economic factors. The uncertainty in climate models, possible lack of data and the complex dynamics and shifts in the climate–socio-economic nexus complicate the planning process. The uncertainties can hinder decision-makers when formulating policies and actions for long-term adaptation and resilience. A more flexible approach and a robust and science-based decision-making process could accommodate a range of scenarios and withstand unexpected shifts. To navigate these inherent challenges, decision-makers must adopt a flexible and adaptive approach. In this respect, the CROSSEU project supports (i) decision-making planning, through integrating a range of plausible future scenarios to explore potential impacts and adaptation options under different climate change and socio-economic contexts, (ii) robust decision-making, through elaborating policy recommendations that are robust to a range of uncertainties and can be adjusted with new information available through the CROSSEU DSS, (iii) risk assessments at NUTS3 level, through assessing the potential impacts of climate-related risks under different climate and socio-economic pathways (RCPs-SSPs) over the 21st century (i.e., 2030, 2050, 2100), and (iv) stakeholder engagement, through involving a diverse range of sectoral stakeholders, including policymakers, scientists, businesses, and communities, in the co-development of the decision-making solution. The project empowers stakeholders with tools and tailored knowledge that strengthen their capacity to address the socio-economic risks of climate change and build a more resilient future for society.

In this context, the CROSSEU Decision Support System (DSS), co-designed with sectoral stakeholders becomes a valuable tool, that incorporates sector-specific requirements and perspectives alongside climatic and socio-economic data. This integration ensures that the outputs of the project are effectively conveyed to both public and private decision-makers through a user-friendly visual interface. The DSS enhances policy design and strategic planning by incorporating complex models and multi-scenario analyses, thereby increasing the capacity for informed and

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effective decision-making with minimised risks. Additionally, the DSS aims to elevate climate change risk awareness among decision-makers, promoting the development and implementation of well-structured and appropriate adaptation and mitigation measures.

Integrating decision-making processes into adaptation assessments facilitates the development of effective and context-specific responses to climate challenges. These processes bridge the gap between scientific analysis, policy development, and on-the-ground action. To achieve seamless integration, adaptation assessments must be designed to incorporate robust decision-making frameworks that promote both flexibility and inclusivity. This involves embedding iterative management, fostering the co-production of knowledge, and ensuring that the resulting policies are actionable and sustainable. In this respect, the CROSSEU project aims to integrate decision-making processes into adaptation assessments through (i) the co-production of knowledge and decision-making tools, through the close collaboration with key stakeholders to ensure that assessments address their specific needs and priorities for the climate-sensitive sectors and at the case study level, and (ii) policy options and recommendations, to support adaptation actions and create enabling environments for climate-resilient development. By fostering collaboration, incorporating flexibility, and prioritizing implementation, the project aims to bridge the gap between research and action, ultimately leading to more resilient societies to climate change risks.

To develop inclusive and effective policies and options, stakeholder involvement must be well-integrated and productive. As adaptation efforts address a large array of challenges and vulnerabilities, and imply multi-faceted approaches, this engagement action aims to create comprehensive and responsive policies for different communities and various sectors.

Stakeholders, including local communities, policymakers, businesses, or non-governmental organisations (NGOs), each hold unique insights into their environments and the challenges they face under climate change. By involving these groups, adaptation strategies can be tailored to reflect the specific conditions and priorities of affected populations. This inclusivity helps ensure that adaptation measures do not overlook marginalised or vulnerable communities, often disproportionately impacted by climate change. Engagement also broadens the knowledge base used for adaptation planning. Traditional and local knowledge provides valuable insights into local context and challenges and could effectively support the co-development of the DSS.

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3.2 Assessing Cost and Benefit

3.2.1 Damage Costs and Benefits, Private and Public Cost

Socio-economic assessments of climate change impacts and risks require a comprehensive evaluation of costs and benefits, encompassing both private and public costs. This section explores the key components of such assessments, including damage costs, benefits associated with adaptation measures, and the distinction between private and public costs.

Damage Costs: Climate change can inflict significant damage costs across various sectors. These costs arise from events like extreme weather (floods, droughts, heatwaves), sea-level rise, and changes in precipitation patterns. Damage costs can be categorized into:

- Direct costs: These are the immediate economic losses resulting from an event. Examples include damage to infrastructure (buildings, roads, bridges), loss of crops and livestock, and disruption to businesses.
- Indirect costs: These are the broader economic consequences that ripple through the economy and society. Examples include loss of productivity, health impacts, and displacement of populations (Halsnæas et al., 2022; 2023; Frame et al, 2020).

Other Relevant Costs

- Social costs: These include impacts on social well-being, equity, and cultural values. For example, climate change can exacerbate existing inequalities and disproportionately affect vulnerable populations.
- Environmental costs: These include damage to ecosystems, loss of biodiversity, and degradation of natural resources.
- Non-market costs: These are difficult to quantify in monetary terms but are nonetheless important. Examples include the loss of aesthetic value, cultural heritage, sense of place, ecosystem values. Health impacts, for example related to mortality caused by extreme heating are also an example of a no-market cost, which in some studies are represented by economic values, and in other studies by other measures.

Benefits of Adaptation and Mitigation

While climate change imposes costs, proactive measures like adaptation and mitigation can generate substantial benefits, but disadvantages can also occur and should be included in assessments. Adaptation benefits: These arise from actions taken to reduce vulnerability and exposure to climate change impacts. Examples include investing in flood defences, developing drought-resistant crops, and improving early warning systems. Benefits may include avoided damage costs, increased resilience, and enhanced well-being. Mitigation benefits: These arise from actions taken to reduce greenhouse gas emissions and limit the extent of climate change.

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Benefits can include improved air quality, reduced health risks, and new economic opportunities in green technologies (Halsnæas et al., 2024; Sharifi 2021).

Private vs. social Costs: Distinguishing between private and public costs is essential in socio-economic assessments. Private costs: These are the costs measures as they arrive to individuals, households, and businesses. Examples include the cost of repairing damaged property, lost income due to business disruption, and increased insurance premiums. Social costs: These are the costs measured from a societal perspective. In addition to the costs that are facing private actors societal costs also include for example externalities on public good such as the environment. In addition to measuring private and social costs it is also important to understanding the distribution of costs between private and public entities is crucial for developing equitable policies and allocating resources effectively (Halsnæes et al., 2023; Berto et al., 2020).

A comprehensive socio-economic assessment necessitates a holistic approach that considers the full spectrum of costs and benefits associated with climate change. This includes evaluating damage costs, the benefits of adaptation and mitigation, and distinguishing between private and public costs. Additionally, incorporating social, environmental, and non-market costs ensures a more nuanced and complete understanding of the implications of climate change for society.

3.2.2 Modelling Perspectives in Assessing Damage Costs and Other Social Impacts of Climate Hazards

The assessment of costs and other social impacts vary with the modelling and methodological approach applied to the case studies.

IPCC, 2001 provides an overview of the perspective in project-based modelling which are relying on very detailed spatial information about assets and activities), sectoral modelling, and macroeconomic modelling.

The project, sector, and macroeconomic levels can be defined as follows:

Project: A project level analysis considers a “standalone” investment that is assumed not to have significant impacts on markets (both demand and supply) beyond the activity itself. The activity can be the implementation of specific technical facilities, infrastructure, demand-side regulations, information efforts, technical standards, etc. Methodological frameworks to assess the project level impacts include cost–benefit analysis, cost-effectiveness analysis, and lifecycle analysis.

Sector: Sector level analysis considers sectoral policies in a “partial equilibrium” context, for which other sectors and the macroeconomic variables are assumed to be as given. The policies can include economic instruments related to prices, trade, and financing, specific large-scale investment projects, and demand-side regulation efforts. Methodological frameworks for sectoral assessments include various partial equilibrium

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models and technical simulation models for the energy sector, agriculture, forestry, and the transportation sector.

Macroeconomic: A macroeconomic analysis considers the impacts of policies across all sectors and markets. The policies include all sorts of economic policies, such as taxes, subsidies, monetary policies, specific investment projects, and technology and innovation policies. Methodological frameworks include various sorts of macroeconomic models such as general equilibrium models, Keynesian models, and Integrated Assessment Models (IAMs), among others. A "trade-off" is expected between the details in the assessment and the complexity of the system considered. For example, a project system boundary allows a rather detailed assessment of GHG emissions and economic and social impacts generated by a specific project or policy but excludes sectoral and economywide impacts. Conversely, an economy-wide system boundary, in principle, allows all direct and indirect impacts to be included, but has little detail in the impacts of implementing specific projects.

3.2.3. Macro-economic Modelling

The main analytical tools used to assess macroeconomic effects from global climate change on the socioeconomic environment are the 'Integrated Assessment Models' (IAMs) and secondly the 'Computable General Equilibrium' models (CGEs). These models are designed to capture complex interactions among the physical, natural and social dimensions of climate change.

Integrated Assessment Models:

Overall, IAMs bring together a description of emissions and climate with a description of how changes in climate affect output, consumption, and other economic variables usually directing the levels of anthropogenic emissions impacting the climate. Within the IAM family, models differ by the complexity of the economic sector or how the climate system is represented, but usually six main elements are represented (Pindyck, 2013): the first three elements constitute the climate science module (emissions, concentrations and temperature), while the last three are part of the economic module (damage costs, mitigation costs and consumption). These components rely on simplified representation of each individual component. Most economic studies of climate change assume that changing temperatures have a direct impact on the level of GDP with for example temperatures affecting the level, not the growth rate, of GDP. However, as discussed in Section 3.1, climate change (from gradual change or extreme events) can cause lasting damage to GDP growth. Moreover, simplistic damage function remains the most speculative element of the analysis and is mostly static (ignoring the dynamical effects of climate change on GDP growth). This shortcoming can be addressed by modelling climate damage in a growth framework (Dietz and Stern, 2015) as in CGE models.

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Computable General Equilibrium (CGE) Models:

A CGE model is a powerful analytical tool used to assess a wide range of economic issues by simulating how an economy responds to changes in policy, technology, or external conditions. These models are particularly effective in evaluating trade policies, such as the impact of tariffs and trade agreements, and environmental policies aimed at mitigating climate change through measures like carbon taxes and cap-and-trade systems. They can also assess the economic effects of transitioning to renewable energy sources, the implementation of energy efficiency measures, and the impact of policies aimed at reducing deforestation, among others. CGE models provide insights into the effects of fiscal policies, including tax reforms and government spending adjustments, on economic activity and income distribution. Additionally, they can analyse labour market policies and sector-specific interventions in the agriculture, industry and service sectors. CGE models can assess the economy-wide implications of external shocks, such as the impacts of climate change on global food production and prices.

By capturing the complex interactions within an economy, CGE models provide policymakers with a comprehensive understanding of the potential outcomes of various policy interventions, thereby guiding more informed and effective decision-making.

3.2.4 Assessment Tools

Cost-benefit analysis (CBA) is an economic decision-making tool that evaluates the costs and benefits of a project to determine its feasibility and cost-efficiency. It involves comparing the expected benefits and costs in monetary terms to assess whether the benefits outweigh the costs. This analysis typically involves three steps: i) identifying and measuring all costs and benefits, ii) assigning a monetary value to these factors, and iii) discounting future costs and benefits to present value (Boardman et al., 2018).

First, CBA requires the identification and classification of all costs and benefits associated with the project. These costs may include direct expenses (e.g., labour, materials, and equipment) as well as indirect costs such as environmental impacts or opportunity costs. Benefits are also identified, including both tangible (e.g., revenue, productivity gains) and intangible ones (e.g., improved public health, ecosystem services) (OECD, 2018).

Once identified, the next step is to quantify these costs and benefits. This stage involves assigning monetary values to both market and non-market resources. The latter are typically estimating by using non-market valuation techniques, such as revealed and stated preference methods (Mishan & Quah, 2020).

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A critical component of CBA is discounting, which adjusts future costs and benefits to their present value. Typically, discount rates range from 3% to 7% depending on the nature of the project and societal factors (Boardman et al., 2018).

After quantifying and discounting, CBA computes the net present value (NPV) by subtracting the total present value of costs from the total present value of benefits. If NPV is positive, the project is typically considered viable (Hanley & Barbier, 2009).

Sensitivity analysis is another essential operational element in CBA. Given that estimates of costs, benefits and discount rates involve some degree of uncertainty, sensitivity analysis examines how the results change when these parameters are varied (OECD, 2018).

Cost effectiveness analysis (CEA) is a special sort of cost benefit analysis where all costs of a portfolio of projects reducing an impact like e.g. adaptation measures are assessed in relation to a policy goal. The policy goal in this case represents the benefits of the projects and all other impacts are measured as positive or negative costs (negative costs, with the exception of the benefits of the policy goal, will correspond to benefits of the policy). The policy goal can for example be a specified goal of risk reduction by adaptation. The result of the analysis can then be expressed as the investment costs of adaptation for a reduction of the number of people affected by a climate hazard and can include other benefits measured in monetary units.

Multicriteria assessment (MCA) is a decision-making tool used to evaluate complex projects or policies by incorporating multiple criteria beyond just financial/monetary outcomes. Unlike cost-benefit analysis, which focuses mainly on monetary valuation, MCA considers diverse qualitative and quantitative factors, such as environmental sustainability, social impact, and stakeholder preferences (Dodgson et al, 2009).

The MCA process typically begins by defining the goals of the assessment and identifying relevant criteria. These criteria represent the key factors that will be evaluated, such as cost, environmental impact, social equity, and risk. Once identified, the next step involves assigning weights to each criterion based on their importance. Weighting allows decision-makers to express preferences and prioritize certain outcomes over others (Greco et al., 2016).

Various methods are available for conducting MCA. One of the most widely used is the Analytical Hierarchy Process (AHP), which organizes decisions hierarchically and uses pairwise comparisons to assign weights to criteria and rank alternatives based on these weights (Ishizaka & Labib, 2011). The Simple Multi-Attribute Rating Technique (SMART) is a more straightforward method that assigns scores directly to alternatives across

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criteria, normalizing these scores and weighting them to yield a final ranking (Montibeller & von Winterfeldt, 2015). ELECTRE (Elimination and Choice Translating Reality) uses concordance and discordance indices to rank alternatives in pairwise comparisons, making it especially useful in decisions with conflicting criteria (Figueira et al., 2009). PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) also compares alternatives pairwise, by using preference functions to establish a ranking (Behzadian et al., 2010). Finally, TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) ranks alternatives based on their distance from an ideal solution, balancing performance against a “best” and “worst” option (Taherdoost and Madanchian, 2024).

3.3. Social and Human Dimensions

The section introduces quantitative and qualitative approaches to measure a broader range of social and human dimensions.

3.3.1 Social and Human Dimensions: Vulnerabilities, Capability Approach and Other Approaches

Climate change impacts human well-being in various ways affecting people's livelihoods, health, and wealth. These impacts are unevenly distributed, exacerbating existing global vulnerabilities and inequalities. Traditional methods of measuring the impact often focus on economic loss and physical damage and do not fully capture the broader social and human dimensions of impacts. The capability approach, developed by Amartya Sen (Sen 1999) and further advanced by Martha Nussbaum, provides a more holistic framework by focusing on individuals' capabilities (ability to do or to be), or genuine opportunities to achieve valuable functionings (what is done), rather than merely on resources (Nussbaum, 2003, 2013; Robeyns, 2003). Here, we are trying to explore the application of the capability approach to measure the impacts of climate events on human well-being.

By integrating socio-economic and environmental factors, this approach offers a nuanced perspective on not only assessing vulnerability and resilience but also impacts of climate events. In the literature, however, the application of the capability approach has mostly been used in the context of disaster management and vulnerability assessment (Boakye et al., 2022; Gardoni & Murphy, 2010; Ton et al., 2019). Therefore, applying the capability approach to understand the human well-being impacts of climate events will be a new addition to the existing literature.

This summary paper outlines a methodology for applying the capability approach, emphasizing the selection of relevant capabilities, data

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collection, and analysis for assessment of impacts of any climate extremes. The proposed methodology aims to enhance understanding of the human well-being impacts of climate events and enable policymakers to develop more effective strategies for risk management.

The Capability Approach (CA) Framework

The capability approach is centered on the idea that human well-being should be assessed by people's capabilities to achieve the kinds of lives they value. This approach shifts the focus from resources and income to the actual freedoms and opportunities individuals have (Nussbaum, 2003). In the context of climate events, this means considering how climate events impact individuals' capabilities to live fulfilling lives.

Key Components of CA

- Capabilities refer to the opportunities individuals have to achieve valuable outcomes (functionings) (Robeyns, 2003). For example, having access to clean water, being able to attend school, or able to maintain a stable income after the climate event
- Functionings refer to what individuals actually achieve in their lives (Robeyns, 2003). While capabilities are about potential freedoms (a set of choices, an ex-ante set), functioning are about actual achievements (a realized or an ex-post activity). Therefore, functionings highlights the importance of not only having opportunities but also realizing them that contribute to well-being (García-Portela, 2024; Robeyns, 2003).
- Conversion Factors are the factors that influence an individual's ability to convert resources into functionings (Robeyns, 2003). They can be personal (e.g., health, skills), social/institutional (e.g., public policies, social norms), or environmental (e.g., geographic location, climate) (Robeyns, 2003). Recognizing and addressing these factors is essential for enabling equitable and effective policies aimed at improving well-being. In climate literature, the social/institutional factors are often referred to as enabling factors.

Here, we mostly deal with the concept of capabilities- how it is impacted by climate events and what can be done to enhance it post a climate events.

Conceptual Framework

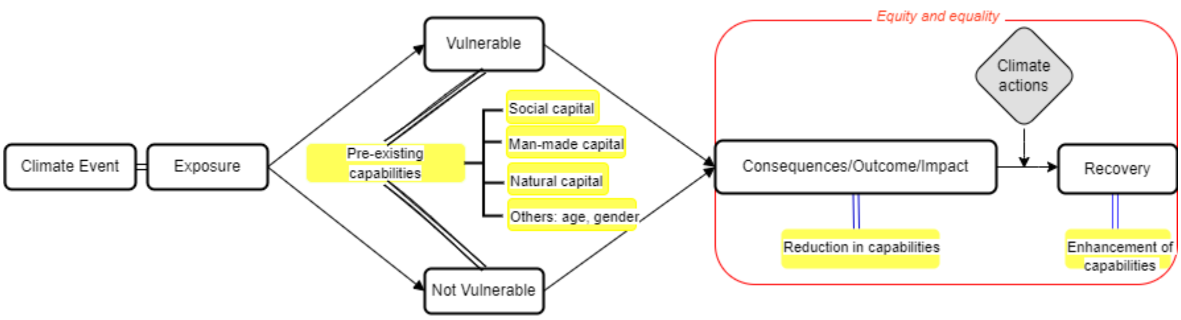

Figure 2: Framework linking capabilities with climate events

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Source: Prepared by authors

Figure 2 links the capability approach with climate events (e.g., flood). When a climate event occurs, people, assets, or infrastructure that are situated in areas susceptible to that event (exposure) are impacted. There are certain groups of people who are more susceptible to the negative consequences of the event (vulnerable), and there are certain groups who are less vulnerable to the impact of that event (less vulnerable). In terms of capabilities, the vulnerable groups lack pre-existing capabilities makes them more susceptible. While not vulnerable, people possess sufficient pre-existing capabilities to withstand the impact and recover effectively. Pre-existing capabilities are the resources, knowledge, and systems that an individual possesses before the event occurs. These can include social capital (social networks, socioeconomic status), man-made capital (infrastructure, technology), natural capital (ecosystem services), and other factors like age, gender.

Consequences/Outcome/Impact of the event can range from physical damage to economic loss and social disruption. Importantly, these impacts can reduce an individual's existing capabilities. Here, we aim to identify specific capabilities that are affected by different climate events, ultimately leading to a decline in human well-being. Identifying the specific capabilities lost or reduced during climate events is essential for effective and equitable recovery. By pinpointing these capabilities, we can tailor aid, resources, and policies to address the most pressing needs, ensuring that recovery efforts reach those most affected in an equitable way. This knowledge also allows us to develop strategies that not only rebuild but enhance capabilities, diminishing devastating impacts from similar events in the future.

The capability approach offers a comprehensive framework for assessing the impact of climate events by focusing on individuals' capabilities. Policymakers should prioritize expanding people's choices and opportunities. The proposed methodology can be replicated in other regions to inform more effective policy responses and promote sustainable development.

3.3.2 Macro-economic Perspective

Climate change is expected to have significant impacts on the human population and income generation worldwide, with effects varying across regions and economic sectors. The World Bank (2020) estimates that climate change will push an additional 68 to 135 million people into poverty by 2030. The human population is expected to face economic disruptions from more frequent and severe weather events, which will reduce productivity and increase recovery costs. In agriculture, altered temperature and precipitation patterns threaten crop yields and livestock productivity, potentially lowering farmers' incomes and raising food prices.

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Health-related costs from climate-induced issues like heat stress and respiratory problems can further reduce labor productivity.

As larger impacts are expected in warmer regions along the equator, the economic burden is expected to fall disproportionately on poorer regions, exacerbating existing inequalities. Moreover, climate-induced migration and displacement can destabilize local economies and income stability. Addressing these challenges will require coordinated mitigation and adaptation efforts to safeguard economic stability and individual livelihoods.

3.3.3 Some qualitative approaches

Social impacts can also be assessed by qualitative methods. In this section, let us illustrate two of the existing methods.

a) Social Risk Analysis

The term "risk", in the context of the social sciences, was first used by the German sociologist Ulrich Beck, who speaks of the "risk society" and attempts to highlight the media, political and scientific characteristics surrounding the notion of the social production of risk. Here, the aim is to highlight the idea that the notion of risk has become central in a society, which, owing to the impact of modernization and its economic and technological processes, is increasingly turned towards the future (Beck, 1986). Beck emphasizes inter alia that wealth is not the fundamental resource for managing risks. Rather, information and knowledge are the basic tools for "managing a risk" (thanks to knowledge, a vague, undetermined "danger" turns into an at least partly known risk, providing a means, as far as possible, of "controlling" it).

In a similar vein, Luciano d'Andrea and Giancarlo Quaranta (d'Andrea, Quaranta, 1996) propose an approach based on the connection between "dangers", "social regimes" and "risks". Dangers are defined as events or processes which are potentially beyond the control of individuals, communities and social groups. Social regimes are the body of norms, institutions, policies and other regulatory frameworks which, taken together, unleash/enhance the capability of social actors to gain control over dangers. Through these social regimes, dangers are turned into risks. This means that in fact risks are dangers which are socially managed/controlled through their identification, awareness thereof and the activation of coping measures.

When a similar approach is used, phenomena such as unemployment, substandard health and education services, social rejection, various types of crime, poor housing and bad territorial management may be considered as social risk factors, which may accompany environmental risk factors like overcrowding, different forms of pollution, housing in flood-prone areas, landslides, etc. When a single individual, family, human group or community accumulates several risk factors (and their intensity), this

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generates varying degrees of social exclusion, which in turn lead these individuals, families, human groups or communities into a process of impoverishment (Mastropietro, 2001).

This represents the theoretical foundation of the Social Risk Analysis (SRA). SRA refers to the assessment of the intensity of some risk factors that are at the origin of a situation of deprivation that can characterize.

- A specific territorial area
- Particularly vulnerable groups (i.e., the elderly, youth, handicapped, chronically ill, women), who, because of their specific condition, tend to suffer damage to a much greater extent than others
- Or both (a vulnerable group in a specific territorial area).

Risk factors that are normally taken into account in an SRA are:

1. Habitat (Low quality of urban housing and housing conditions of the population)
2. Health (Low quality of health prevention and promotion processes)
3. Work (Low access to employment)
4. Intelligence (Inadequate promotion and defence of local human resources)
5. Crime (Presence of insecurity conditions in the territory)
6. Gender (Lack of valorisation of female human resources)
7. Family (Crisis of the family structure)
8. Communication (Difficulty in accessing information and communication systems)
9. Public administration (Low quality of public administration)
10. Institutional disorder (Difficulty in managing social processes by institutions)
11. Social security (Low levels of social security)
12. Social abandonment (Lack of provision of assistance and protection services)
13. Consumption (Lack of access to non-essential goods)

Specific indicators for each one of these risk factors should be identified. For instance, for the factor "Habitat" the following indicators can be taken into account.

- housing built in inappropriate locations such as riverbanks or ditches, flood zones, landslide slopes, etc.
- overcrowded urban areas
- overcrowded housing (with more than three people per room)
- housing in poor condition
- landfills and open sewers
- dangerous industrial installations (or similar) close to housing
- air pollution
- noise pollution
- poor presence of parks and green areas

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Globally, 88 indicators are identified with reference to the 13 risk factors (Mastropietro, 2001). In each territorial area (a village, an urban agglomeration, a neighbourhood, etc.) in which the SRA is applied, the occurrence or otherwise of each of these 88 indicators is verified. The intent is not to calculate a synthetic risk index, but to represent, in each territory, what the relevant risks are. This approach could be considered complementary (and not at all a substitute) to quantitative methods (e.g. adopted on COACCH aimed to produce an improved downscaled assessment of the risks and costs of climate change in Europe (also in relation to social events, such as migration, on established socio-economic systems) (COACCH. 2021).

b) Social impact assessment

The notion of a social impact assessment (SIA) was designed in conjunction with evaluations of programmes, policies and projects of public interest as an "arm" of the environmental impact assessment (EIA), in terms of their impact on societies/social actors (UNEP, 2002). There is no officially recognized or universally shared definition of an SIA, and the debate on how to conduct an SIA has evolved over time, starting during the 1970s (Quinti, 2016). Even though the debate is still open, today, the social impact assessment may be defined as follows: "The SIA is the process whereby one develops an analysis, follow-up and management of the expected and unexpected social consequences, both positive and negative, of both planned interventions (policies, programmes, plans and projects) and unplanned ones. In addition, the SIA is designed to shed light on the processes of social change invoked by these interventions, as its main aim is to develop a more equitable and sustainable biophysical and human environment." (Vanclay, 2003)

In this frame, social impacts may be defined as the consequences for people of an action which modifies their lifestyle, working mode, relations, organization and role as individuals and members of society (UNEP, 2003). This definition encompasses, inter alia, socio-psychological changes, which affect for example people's values and attitudes and their perceptions of themselves and their community and environment. Some SIA practitioners consider that social impacts include both personal living conditions (e.g. stress and other forms of disruption) as well as changes which impact society as a whole (e.g. overpopulation, pressure on infrastructure, poverty) (World Bank, 2003). A composite (albeit non-exhaustive) list (Vanclay, 2006) of potential social impacts is reported below. It represents a possible check-list. However, its relevance in every given situation or country should be checked. Moreover, numerous impacts among those listed are not easy to measure and require the analysis of a number of variables.

Individual and family:

1 Death, death of a family member

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2 Arrest, imprisonment, detention, torture, intimidation or other human rights violations inflicted upon an individual

3 Reduced availability of food and an adequate diet

4 Reduced control of fertility (availability of contraception and self-reliance)

5 Reduced level of health and fertility (child-bearing ability)

6 Reduced mental health, increased stress, anxiety, alienation, apathy, depression

7 Uncertainty as to impacts, development opportunities and social changes

8 Personal security status, exposure to risks

9 Experience with stigmatization and deviancy

10 Decline in the perceived quality of life

11 Decline in living standards or level of affluence

12 Worsening of the economic situation, drop in the value of property income

13 Decrease in autonomy, independence, security and livelihood

14 Change in status or type of employment, or redundancy

15 Fewer opportunities for work, potential diversity and employment flexibility

16 Moral violence, blasphemy, religious insult, desecration of sacred sites

17 Pushback (objection/opposition to the project), NIMBY attitude

18 Dissatisfaction with a project which has not met high expectations

19 Nuisance (dust, noise, foreigners, crowds)

20 Disruption of everyday life, lifestyle (changing habits)

21 Decline in the value of environmental commodities

22 Perception of the community, community cohesion, integration

23 Community's identification and relationship with the place (belonging)

24 Change in attitude towards the local community, level of satisfaction with the neighborhood

25 Disruption of social networks

26 Modification of family structure and stability (divorce)

27 Domestic violence

28 Gender relations within the family

29 Modified cultural values

30 Modified perceptions of personal health and security, risk, fear of crime

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31 Modified leisure opportunities

32 Housing quality

33 Impact on the homeless

34 Density and crowds

35 Aesthetic quality, insight, visual impacts

36 Workload, amount of work required to survive/live decently

Community and institutions:

1 Death of people in the community

2 Violation of human rights, of freedom of expression

3 Adequacy of the community's physical infrastructure (water supply, sewers, services and commodities)

4 Adequacy of the community's social infrastructure (health, well-being, education, libraries, etc.)

5 Adequacy of the community's housing

6 Workload for institutions, local authorities, regulatory bodies

7 Cultural integrity (maintenance of local culture, tradition, rites)

8 Rights to resources and access thereto

9 Influence on cultural heritage and other major archaeological, cultural or historical sites

10 Loss of the local language or dialect

11 Cultural impoverishment

12 Equity (economic, social, cultural)

13 Changes in problems of equity/social justice involving minority or indigenous groups

14 Gender relations in the community

15 Economic prosperity

16 Dependence/autonomy/diversity/viability of the community

17 Unemployment level in the community

18 Opportunity cost (loss of other options)

19 Real crime

20 Real violence

21 Social tensions, conflicts or serious divisions within the community

22 Corruption, credibility and integrity of the government

23 Level of community participation in decision-making

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24 Social values of cultural heritage and biodiversity

The above-list may serve as a reference point, but, as has already been emphasized, a specific repertory of potential social impacts should be prepared on a case-by-case basis.

When defining or conceptualizing social impacts, it may be useful to bear in mind the following categories (which may change from one community to another, or over time) (Vancley, 2003).

— People's lifestyle: how they live, work and interact on a daily basis

— Their cultural identity: habits, obligations, values, language, religious beliefs, customs, aesthetics and cultural heritage, feeling of belonging, security and liveability, aspirations for the future

— Their community: cohesion, character, stability, services and infrastructures, volunteer organizations, activity networks

— Their political system: the level of people's participation in decision-making, as well as the way in which resources are shared and distributed in order to promote democratization

— The environment, air and water quality, availability and quality of food, the disaster risk level, health quality, as well as access to and control over natural resources

— Health: including physical, mental, social and spiritual well-being, and not only considered as the absence of disease

— Personal and property rights: guarantees to ensure that people are not economically affected or disadvantaged in terms of civil and political liberties;

— Fears and aspirations: their perception of security, their fears with regard to the community's future, as well as their own aspirations for the future and for future generations.

The next step is to determine which impacts may effectively be verified (in the case of an ex-ante analysis) or which have been or are being verified (in the case of an ongoing, terminal or ex-post analysis). In the majority of cases, all that can be done is to determine whether an impact is (or may be) present or not and to describe it, even if quantification is not possible. In this respect, opting for qualitative methods makes it possible to gather viewpoints and testimony from stakeholders, such as representatives from:

- Ministries, public departments and bodies
- Communities at risk
- Scientific institutes
- Non-governmental organizations and other civil society entities
- The private sector
- The media.

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One particularly suitable method is the Coordinated, Multilateral and Interactive Consultation approach (Cancedda, 2005), whereby all stakeholders are consulted and their viewpoints are compared interactively. If possible, this is done by convening a focus group where stakeholder representatives are both present and interact directly with each other with the help of a moderator. If this is not feasible, this is done through successive consultations of stakeholder representatives making it possible to gradually identify the viewpoints as they emerge (all are informed of the viewpoints expressed by the persons consulted previously in relation to each social impact). The interaction generated by this approach (or similar methods) provides an opportunity to step back and reconsider the purpose of the action/project/programme or event whose social impact is being evaluated.

As far as possible, it would be appropriate to not only identify and describe impacts which can actually be verified (from an ex ante perspective) or which have actually been verified (from an ex post perspective) but also to quantify these impacts (also through "proxy" indicators, e.g. that is, they do not directly measure the phenomenon but only measure part of it or measure a phenomenon which is correlated, that is, for which we assume that the change or, better still, the variation over time or in space is similar) (Quinti, 2016).

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4. Case studies

The 8 case studies focus on four of Europe's key climate hazard categories, including both sudden onset extreme events, such as storms or heatwaves, and slow onset processes, such as droughts or snow-related (which can also produce sudden extreme events such as avalanches). Two STLs address the impact of extreme events in the cross-sectoral multi-hazard risk framework and the indirect climate change impacts and spillover effects to Europe. The emphasis of STLs is on four climate-sensitive systems (i.e., urban, rural, mountain, and coastal regions), across all the CROSSEU sectors which are consistent with the key focal areas proposed in PESETA IV.

In this section, we provide a short description of the event-based storyline, associated CCHs along with the methodological frameworks for each of the 8 case studies.

#1 HEAT

Event based storyline (STL)

Temperatures in Europe are rising at twice the rate of the global average. Many negative climate-related health impacts have already been observed across Europe due to observed climate change, with risks projected to increase as temperatures increase in the future (van Daalen et al., 2024; García-León et al. 2024).

Significant risk of heat-related mortality and morbidity can be observed across the whole European continent. The magnitude of the risk differs depending on the climate characteristics, demographic structure and socio-economic characteristics that differentiate population groups most vulnerable to climate-related risks (Masselot et al., 2023). Fig 3 shows a north-south gradient in annual heat-related mortality rates (per 100 000 inh.). Despite the largest proportion of heat-related mortality in the south-eastern Europe, no region is immune to excessive heat.

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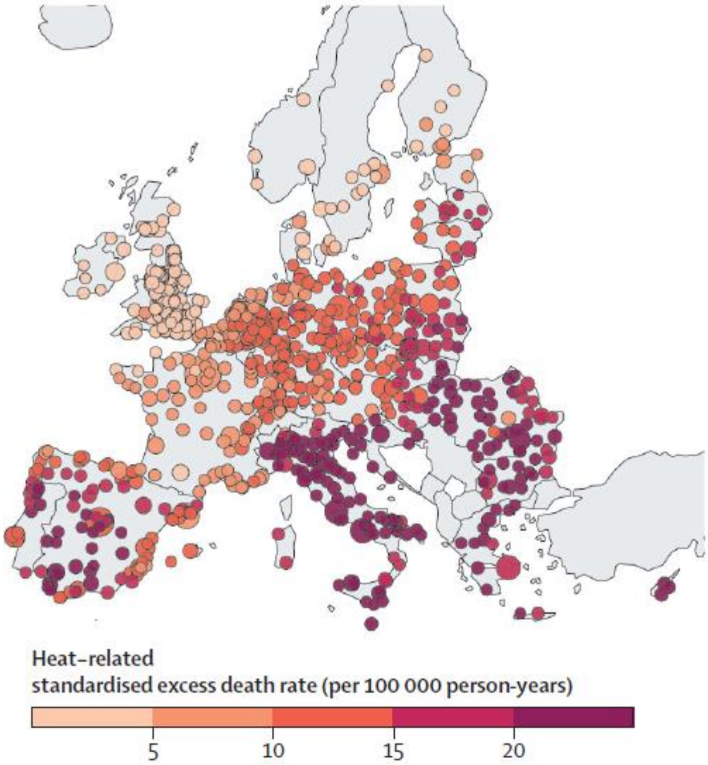

Figure 3: Annual impact of heat on mortality across European cities (Masselot et al. 2023).

Record breaking heatwaves have been observed across Europe during the recent decade (2010-2019), and attributional studies suggest that the likelihood of occurrence of European heatwaves like the one in 2019 has been 2 to 10 times higher due to climate change (Vautard et al. 2020). Increasing frequency and intensity of heatwaves affects human health across Europe (van Daalen et al., 2024). For example, a case study from Prague, Czech Republic suggests that the risk of heat-related mortality in 2010–2019 was twice as high as in the previous three decades (Urban et al. 2022 Fig. 4). Especially a record-breaking summer 2015 regarding the intensity as well as duration of heatwaves in the Central Europe (Lhotka et al. 20224) had an unprecedented impact on heat-related mortality in Czech Republic and Prague (Urban et al. 2020, Urban et al. 2022; Fig. 5). This finding highlights the importance of assessing the adaptive capacity of health sectors in individual countries while using as recent as possible datasets.

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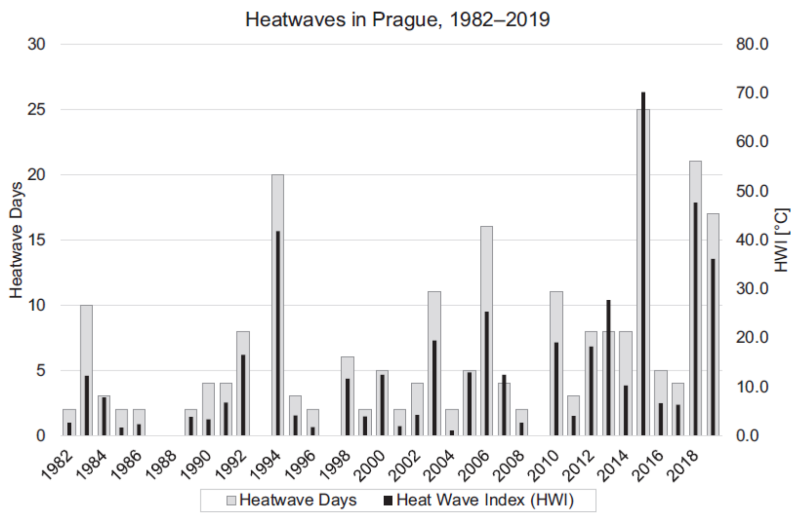

Figure 4: Duration (Heatwave Days) and intensity of heatwaves (Heat Wave Index) in Prague, 1982–2019 (Urban et al. 2022).

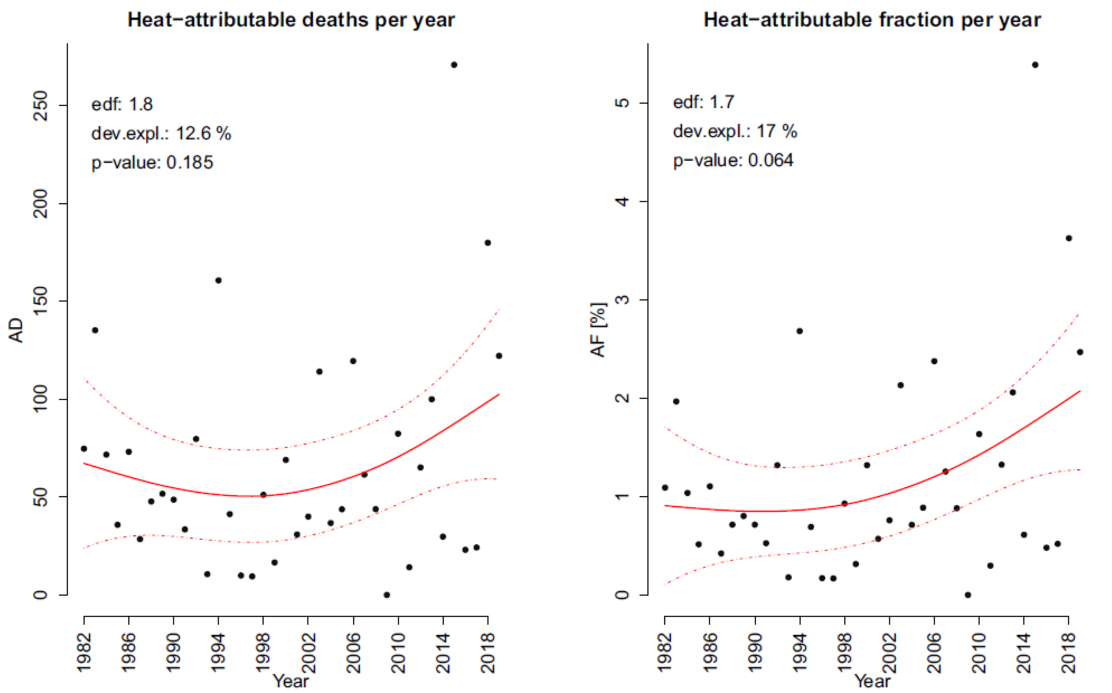

Figure 5: Smoothed (generalised additive model) trend estimations of seasonal heat-attributable deaths (left) and fraction of total deaths (right), respectively, during May–September 1982–2019. Edf: shows estimated degrees of freedom for the smoothed trend. Dev. expl.: indicates proportion of the null deviance explained by the model. P-value: indicates significance of the smoothed trend estimate (Urban et al. 2022).

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Climate Change hotspots (CCH)

Hotspot 1: Prague, Czech Republic

Jánoš et al. (2023) suggests that Prague and Southern Moravia Region (both NUTS 3 level regions) are current CCHs regarding the overall heat-related mortality risk in the Czech Republic (Figure 6). Elderly and women are most at risk (Figure 7) (Jánoš et al. 2023, Vésier and Urban 2023).

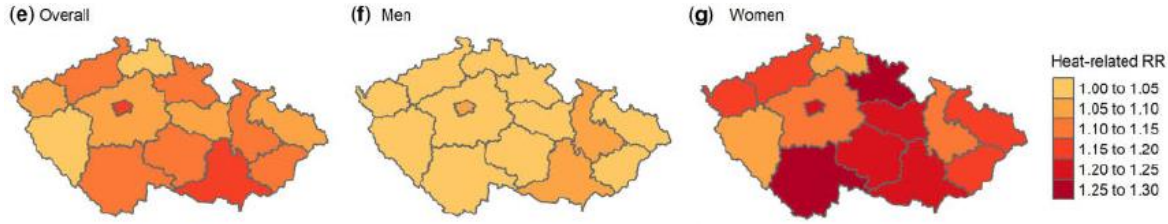

Figure 6: Spatial variation in heat-related mortality risk in Czechia (Jánoš et al. 2023).

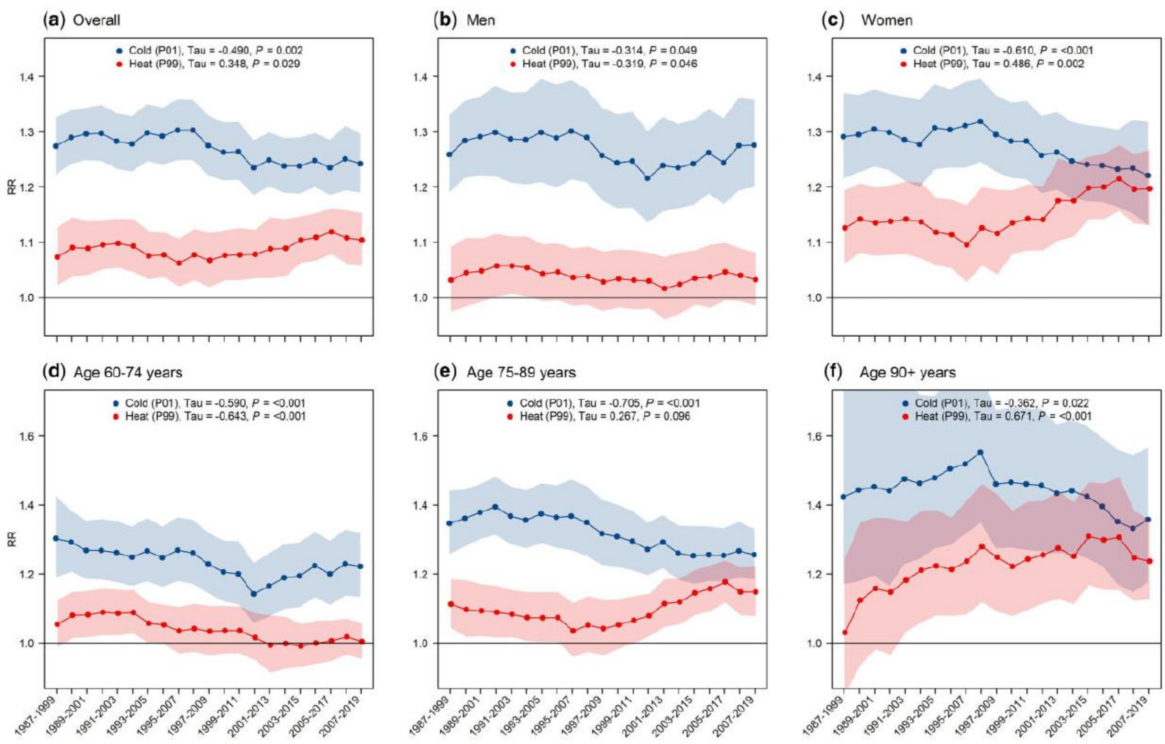

Figure 7: Relative risk of death at the 1st (cold) and 99th (heat) temperature percentiles of the whole study period from the model with subsets of 13-year moving periods (Jánoš et al. 2023).

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Hotspot 2: London, United Kingdom

For the UK, summers as hot as 2018 (the joint warmest summer on record) are currently expected to occur in up to 20% of years under future scenarios of climate change, whereas they would be expected in less than 10% of years only a few decades ago. Geographically, the levels of warming are projected to be highest in the South-East and London. It has been estimated that there is currently a 5% chance of reaching a maximum temperature of at least 35.4°C in London per year (CCC, 2021). This is further amplified due to London's Urban Heat Island (UHI), with an UHI effect of up to 7 degrees recorded for the region (CCC, 2021).

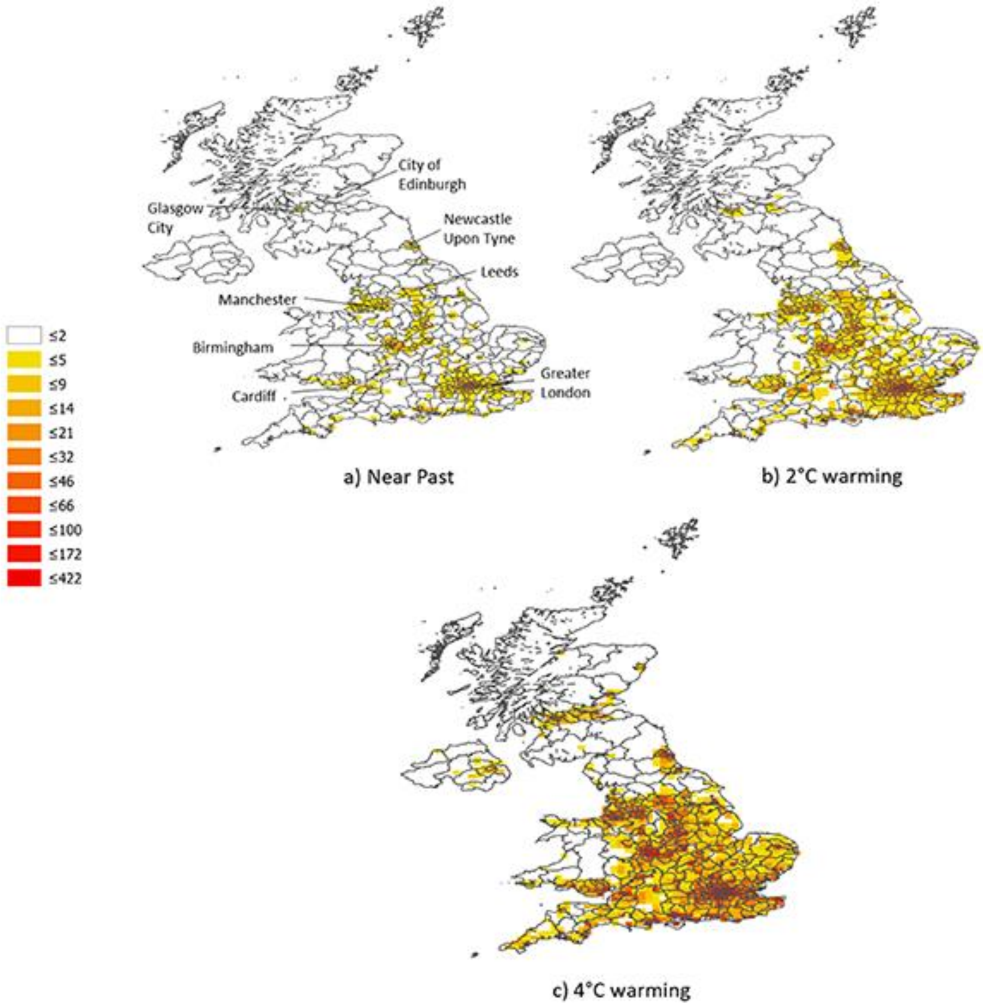

Figure 8: Spatial pattern of average annual heat-related deaths in the UK for all ages.

Given the population, density, socio-economic conditions, UHI effect and changes in climate projected for London, it is considered as a second hotspot for analysis under the heat storyline (Figure 8).

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The objective of this case study

The objective of the hotspot 1:

- to analyse the links between spatiotemporal dynamics of heatwaves and detailed mortality data sets in the Czech Republic,
- to estimate the future impact of heatwaves based on region and population group specific exposure-response curves,
- using socioeconomic and demographic data at the NUTS3 level, identify regions and population groups that are potentially most vulnerable to the impact of increasing frequency and intensity of heatwaves in the future climate.

Application of the methodology framework

The risk of heat-attributable mortality due to selected diseases during the recent hot decade (2010–2019) are identified. We will use up-to-date mortality datasets from the Czech Republic (CZU) providing individual records up to the NUTS 3 administration level divided by gender, age and cause of death. The exposure-response functions of heat-related mortality will be identified using state-of-the-art epidemiological approaches (distributed lag non-linear models and multilevel meta-regression models Sera et al. 2019, Vicedo-Cabrera et al. 2019) and high-quality climate datasets (ERA 5, Hersbach et al. 2023).

Statistical models will be employed to analyse the associations of heat-related mortality risk with selected demographic, environmental, SE and climatic variables during the study period (2010-2019). Consequently, based on different RCP scenarios (EURO-CORDEX), high-resolution projections of the CC impact on heat-related mortality through the 21st century in selected countries will be projected. Based on the literature review of national climate change adaptation policies (MZP 2017) and national socioeconomic and demographic projections (Kotlář et al. 2023, CSU 2024) possible socio-economic scenarios will be developed to estimate the impact of CC on heat-related mortality among vulnerable population groups.

Focusing on all-cause daily mortality data on the NUTS 3 administration level and using the state-of-the-art epidemiological approaches represent the main innovative aspects of the methodology framework compared to COACCH (Ščasný et al. 2020) and PESETA IV (Neumann et al. 2020) projects that will provide a new insight to the links between extreme heat and mortality at the regional level.

The objective of the hotspot 2:

- to analyse the links between spatiotemporal dynamics of heatwaves and detailed mortality data sets in London, UK.
- to estimate the future impact of heatwaves based on region and population group specific exposure-response curves,
- using socioeconomic and demographic data at the NUTS3 level, identify population groups that are most vulnerable to the impact of increasing frequency and intensity of heatwaves in the future climate.
- Provide a comparative analysis of risk across London and Prague and explore the different socio-economic and climate factors responsible.

The risk of heat-attributable mortality during the recent hot decade (2010–2019) will be identified following the same modelling approach as for the Czech Republic (CZU) reported above.

Application of the methodology framework

The focus will be on the health sector, with the framework use to support the identification of heat related mortality risk at regional levels and use of information within health planning.

Table 1: Application of conceptual framework for case study 1 - figure 1

Step 1: Climate and socioeconomic scenarios	
Climate scenarios	Scenarios: RCP scenarios (CRODEX) - RCMs RCP4.5 and RCP8.5 Years: Impacts per decade from 2030s to 2090s
Demographic scenarios	Projections of the age structure in the regions (EUROSTAT, Czech Statistical Office, National Stat. Offices)
Socioeconomic scenarios	Relevant socioeconomic scenarios for the case study are based on the literature review of national climate change adaptation policies and national socioeconomic and demographic projections and compare them with no adaptation scenarios

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Adaptation scenarios	Changes in the exposure-response function based on demographic structure, socioeconomic factors, and other adaptation factors are applied.

Step 2: Spatial data integration	
Description	Climate and health data will be aggregated to NUTS 3 regions.

Step 3: Impact assessment	
Description	Heat-attributable mortality fraction (excess mortality) will be quantified based on the exposure-response function, using distributed lag non-linear models and multilevel meta-regression models (Sera et al. 2019, Vicedo-Cabrera et al. 2019)

Step 4: Risk assessment	
Description	Heat-related mortality risk. We will focus on indirect cost measures such as the number of heat-related deaths.

Step 5: Adaptation options	
Description	Changes in exposure-response function based on results for various demographic and socioeconomic groups

Step 6: Decision support

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Description	Qualitative and quantitative assessments of the impact of adaptation options (based on socioeconomic and demographic projections, and planned climate change adaptation strategies)

#2 DROUGHT

Event based storylines (STL)

The European Climate Risk Typology framework for drought focuses on identifying and categorizing drought-related risks in Central and South-eastern Europe (Figure 9). This framework provides detailed background information on the primary hazards associated with drought in these regions, aggregated at the NUTS3 (762 NUTS3 regions for the study area) level, which is a regional classification system used within the European Union.

Figure 9: CS#2 – Study area.

The climate risk typology for drought impacts across Central and South-Eastern Europe shows a region facing diverse and increasingly severe environmental and economic challenges due to rising drought frequency and intensity.

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Central Europe experienced significant agricultural, and forestry impacts due to escalating drought conditions. During the extreme 2018-2019 drought, staple crops saw production declines of 20-40%, with lasting impacts on soil quality and increased demand for irrigation that strained water supplies across sectors. Forests in Central Europe also suffered increased defoliation, especially among broadleaves, with drought-induced vulnerability leading to pest outbreaks and decreased timber yields (Conradt et al., 2023; Knutzen et al., 2023). Water scarcity further escalated competition between agricultural, industrial, and municipal uses, compounding the region's vulnerability (Hanel et al., 2018).

Climate risk in Central Europe also extends to socio-economic impacts; studies by Dlhopolec et al. (2023) indicate that drought-driven declines in agricultural and forestry productivity carry notable economic consequences, impacting local economies and contributing to inflation in food prices.

South-Eastern Europe is highly vulnerable to drought due to its dry climate, with increasing episodes exacerbating water scarcity and affecting agriculture, which is highly dependent on irrigation. The 2022 drought was particularly devastating, leading to notable yield reductions in key crops such as maize and sunflower. In some Carpathian-Balkan countries, the agricultural revenue losses in 2022 reached levels equivalent to 1-2% of GDP (Pinke et al., 2023). Additionally, drought contributes to accelerated desertification, particularly in arid regions, further lowering land productivity and impacting food security (Borrelli et al., 2020).

The droughts have also compounded environmental stress in water-scarce areas, making it difficult to sustain water supplies for both drinking and energy production. This ongoing water scarcity threatens the economic stability of agriculture-dependent communities in South-Eastern Europe, highlighting the need for adaptive strategies and investment in drought resilience (van Daalen et al., 2024). Typology also reveals a broader economic and social impact across these regions, emphasizing the importance of adaptation. Central Europe faces economic losses in agriculture and forestry that affect both local economies and the broader European supply chain (Wang et al., 2023). South-Eastern Europe is further impacted by escalating land degradation risking food security and heightening competition for water resources, thus demanding improved water management policies and climate adaptation measures (Borrelli et al., 2020). In summary, the climate risk typology across Central and South-Eastern underscores the urgent need for adaptive land management practices, investment in drought-resilient crops, and enhanced water management policies to mitigate the compounded impacts of frequent droughts driven by climate change.

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Climate Change hotspots (CCH)

Hotspot 1: Brandenburg, Saxony, Bavaria, and Baden-Württemberg in Germany

Germany has been experiencing increasingly frequent and severe extreme weather events, such as heatwaves, droughts, and flooding. These events are expected to intensify with climate change. The droughts in Germany from 2018 to 2023 were widespread, with the most significant impacts felt in eastern, southern, and central regions like Brandenburg, Saxony, Bavaria, and Baden-Württemberg. These areas, highly dependent on agriculture, suffered greatly from reduced crop yields, economic losses, and environmental degradation, particularly in forested areas. As climate change continues to intensify, these regions remain at the forefront of Germany's efforts to adapt to extreme weather events.

Hotspot 2: South Moravia, Vysočina Region, Central Bohemia and Ústí and Labem and Pardubice Regions from Czech Republic

Between 2018 and 2023, the Czech Republic experienced severe drought conditions, affecting multiple regions and sectors. Drought persisted in 2019 in central Bohemia, south Moravia, and north-western regions. The compounded effects of the 2018 drought meant groundwater and reservoirs did not recover, intensifying agricultural and ecological challenges. By mid-2019, over 99% of the country was experiencing drought conditions, with groundwater levels reaching historic lows in some areas (Figure 10) (Metner et al, 2023).

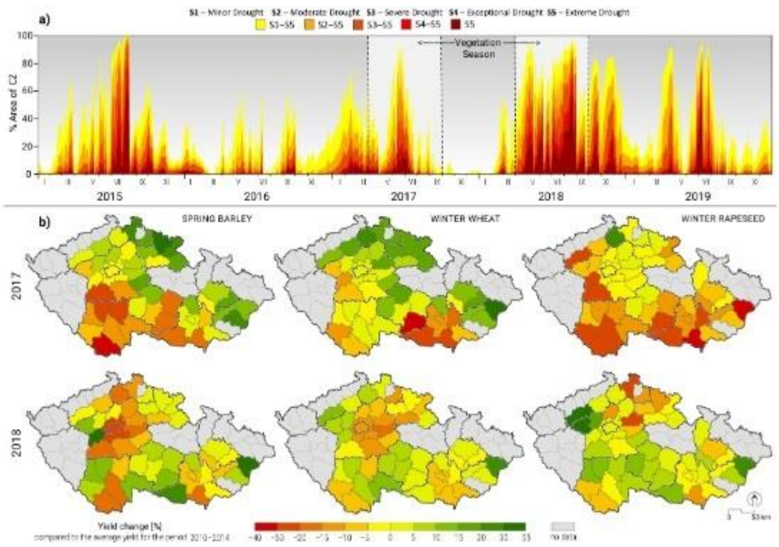

Figure 10: (a) Daily proportion of the Czech Republic (CZ) affected by drought intensity categories [14] between 1 January 2015 and 31 December 2019; (b) yield deviations in NUTS4 regions for winter wheat, spring barley and winter rapeseed during the droughts of 2017 and 2018, expressed as yield anomalies [%] from the 2010–2014 mean.

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Although conditions improved slightly, in 2021, the central and southern regions of the Czech Republic continued to face challenges from decreased water retention due to overexploitation and poor management. Adaptation measures began gaining traction to address recurrent drought threats. In 2022, the Czech Republic faced significant drought conditions, primarily exacerbated by below-average precipitation and rising temperatures. In 2023, drought conditions persisted and intensified, driven by a combination of low rainfall, extreme heat waves, and increased water demand (Figure 11). The Sázava and Elbe River basins recorded historically low water levels, prompting government warnings about water rationing. Ecosystems dependent on river flows faced stress, with fish mortality events reported in several rivers due to reduced oxygen levels and high temperatures (Balcan Insight, 2023).

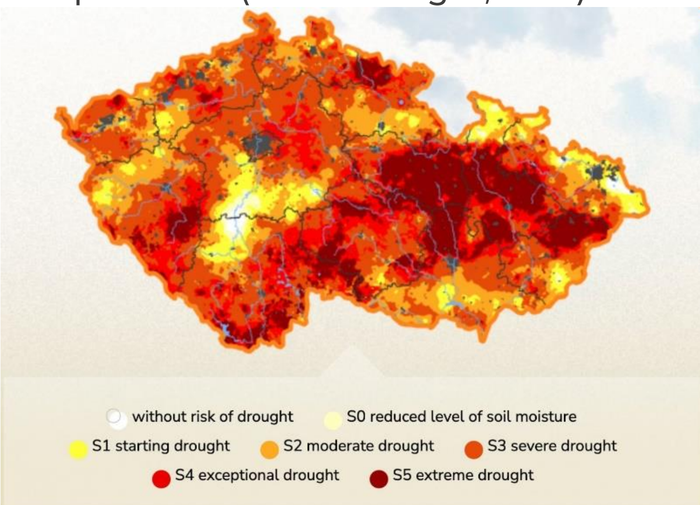

Figure 11: All degrees of drought strength and their spatial representation within the Czech Republic during week 28 of 2023

South Moravia-Frequent droughts have led to a long-term decline in soil moisture and groundwater levels, further exacerbating water scarcity during heatwaves. Agricultural sensitivity and limited water retention capacity make it a primary target for drought-related studies in the region. The Vysočina region has experienced notable declines in forest health, particularly among spruce stands, due to drought stress and pest outbreaks such as bark beetles. Agricultural systems here face challenges from reduced water availability and shallow soils that struggle to retain moisture. Its role as a significant forestry and agricultural area makes it economically vulnerable to droughts. Central Bohemia has seen recurrent reductions in river flow, particularly in the Elbe and Vltava rivers, which are crucial for agriculture, hydropower, and industrial water use. Urban areas within this region, including Prague, also experience water supply challenges during prolonged drought periods. Its proximity to urban centers amplifies socio-economic impacts, as water demand continues to rise amidst declining resources. Ústí nad Labem and Pardubice regions are significantly impacted by agricultural and hydrological droughts, which

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have caused declines in crop yields and strained water availability for irrigation and drinking purposes. Low groundwater recharge rates due to reduced rainfall exacerbate long-term vulnerability to climate-induced droughts

Hotspot 3: Central Poland (Łódź and Greater Poland), Western Poland (Lubusz and Lower Silesian), Northern Poland (West Pomeranian), and Southern Poland (Lesser Poland and Silesian)—Poland
Poland, characterized by diverse precipitation patterns, has been increasingly affected by droughts due to rising temperatures and changing climate patterns. Between 2018 and 2023, drought became a pressing issue, affecting agriculture, water resources, and ecosystems. The period from 2018 to 2020 was particularly severe, aligning with a Europe-wide drought event considered the most intense in over 250 years. This multi-year drought revealed vulnerabilities in Poland's soil, agriculture, and water systems (Jędrejek et al., 2022). It particularly affected central Poland, which is more vulnerable due to its lower annual precipitation (under 500 mm) and soil properties. This drought also had long-term impacts on groundwater levels and river flows, marking a transition from agricultural to hydrological drought phases (Jędrejek et al., 2022; Ziernicka-Wojtaszek, 2021) (Figure 12)

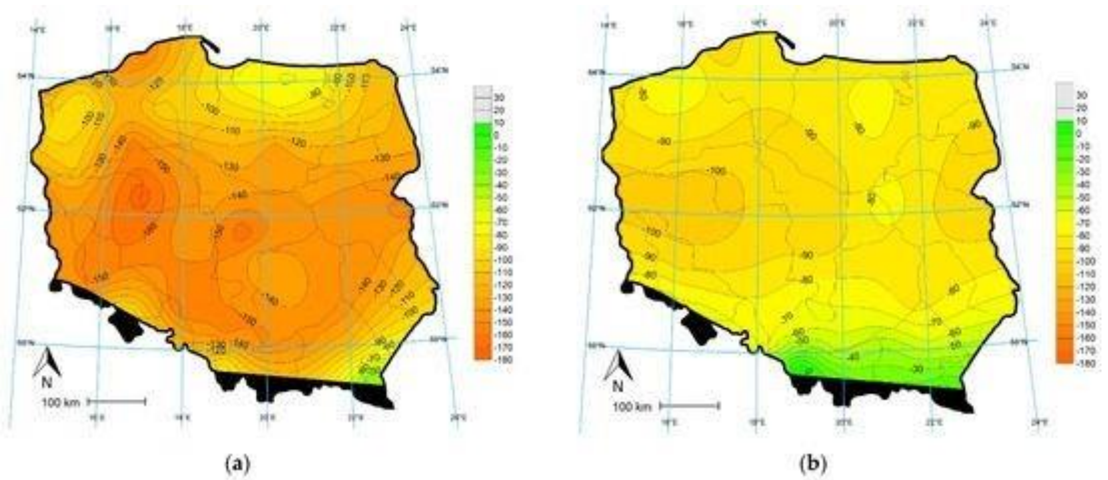

Figure 12. Climatic water balance (CWB) in August: (a) 2019; (b) 1981–2010. White color—phenomenon does not occur. Black color areas above 500 m above sea level.

In 2023, Poland faced continued challenges from drought, with particularly severe impacts on its water systems and agriculture. A major concern was the significant drop in water levels of Poland's primary rivers

The regions identified as most affected by drought in Poland during 2018–2023—Central Poland (Łódź and Greater Poland), Western Poland (Lubusz and Lower Silesian), Northern Poland (West Pomeranian), and Southern Poland (Lesser Poland and Silesian)—were chosen based on their unique vulnerabilities to drought conditions and socio-economic contexts. These

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regions were identified as drought CCHs due to their: high exposer to extreme events (repeated cycles of severe drought, compounded by rising temperatures, created a pattern of vulnerability), economic reliance on water-dependent sectors (agriculture, hydropower, and tourism were deeply affected, creating economic instability), social and environmental strains (rural communities struggled with declining agricultural viability, while water scarcity stressed ecosystems and local economies), projection of long-term risk (trends in climate data pointed to increasing drought frequency, making these regions harbingers of Poland's broader climate challenges) (Jędrejek et al., 2022; Ziernicka-Wojtaszek, 2021).

Hotspot 4: Dobrogea, Bărăgan Plain, Oltenia Plain and Moldavia in Romania

Romania experienced significant drought challenges between 2018 and 2023, with impacts on agriculture, water resources, and the broader economy. The severity of drought varied by region and year, intensifying the need for better water management and resilience planning. Between 1958 and 2023, the annual average temperature in Romania increased by approximately 2.11°C, exceeding the global average rise (+1.81°C) by 0.30°C and the European average (+1.99°C) by 0.12°C. The largest drought-affected areas have been recorded over the past two decades, with notable peaks during the periods 2018–2020 and 2021–2023. At the national level, the longest drought was recorded between October 2018 and March 2021, peaking in May 2020. The second most severe event occurred between March 2022 and December 2023, lasting 22 months, with its peak in August 2022 (InfoClima, 2024).
Dobrogea and the Bărăgan Plain are chosen as drought hotspots in Romania due to their semi-arid conditions, low rainfall, prolonged dry spells (during the growing season, where the absence of rainfall over weeks or even months leads to significant water deficits), and vulnerability of agricultural systems (rain-fed agriculture predominates, the absence of sufficient irrigation infrastructure exacerbates the impacts of drought) (Angearu et al., 2020; Angearu et al., 2018). These factors, along with the socio-economic consequences on agriculture, water resources, and energy production, make them critical regions for monitoring and addressing the impacts of drought. Moldavia experiences lower-than-average precipitation, especially during the summer months, which significantly impacts the availability of water. Meteorological droughts are common in this region due to the lack of rainfall during critical agricultural periods. In years with inadequate rainfall, Moldavia faces deficits that directly affect crop health and productivity. The combination of insufficient rainfall and high evaporation rates exacerbates the agricultural drought in Moldavia. The region's dependence on rain-fed agriculture makes it particularly vulnerable to water scarcity, as irrigation infrastructure is often limited or insufficient. As a result, key crops like wheat, maize, and vegetables suffer from water stress, leading to reduced yields or total crop failure during prolonged dry spells. The European

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Environment Agency (EEA) and studies conducted by Bojariu et al. (2020) confirm that Moldavia is particularly vulnerable to climate-induced droughts. The Oltenia Plain, in southwestern Romania, is a significant drought hotspot due to its semi-arid climate, low and irregular rainfall, and high evaporation rates. The region faces water scarcity, exacerbated by high summer temperatures and intense evaporation, which reduces moisture available for crops (Ontel et al, 2023). Its flat terrain and limited natural water resources (like rivers and lakes) compound this issue. During droughts, even the Danube River suffers reduced flow, affecting both irrigation and drinking water supplies. Oltenia's agricultural sector, heavily dependent on irrigation, suffers from insufficient infrastructure, leading to severe crop damage during droughts. The region is especially vulnerable due to its reliance on rain-fed agriculture for crops like maize, sunflowers, and wheat. The lack of efficient water management systems further aggravates drought impacts. This leads to crop failures and financial strain on farmers. Additionally, reduced water availability affects both agricultural and domestic water use, and also energy production, as reduced river flow diminishes hydropower output.

Objective of this study

The objective of this study focuses on assessing the far-reaching effects of drought on various economic sectors, communities, and environmental resources in the region. Specifically, it aims to analyze how drought conditions have impacted agriculture, water resources, and the overall economy in countries from Central and South-Eastern Europe. Given the region's reliance on agriculture and the increasing frequency of extreme weather events, the study also seeks to examine vulnerabilities within these societies and their ability to adapt to prolonged dry spells.

This study aims to:

- Assess Regional Vulnerability: Evaluate each region's vulnerability to drought, focusing on agricultural, water resources, and economic activities that are drought sensitive. This analysis includes examining factors like dependency on agriculture, water scarcity levels, and the infrastructure available for water management at the local level.
- Quantify Economic Losses: Using high-resolution data at the NUTS 3 level, the study seeks to estimate the direct and indirect economic losses attributed to drought. This includes analysing reductions in crop yields, decreased productivity in sectors like energy and industry, and increased costs associated with drought mitigation measures.
- Map Socio-Economic Impacts: By identifying socio-economic indicators and comparing them across regions, the study aims to create maps and data visualizations that highlight areas most affected by drought. This spatial analysis can help policymakers

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target assistance where it's most needed and improve resilience strategies in vulnerable areas.

- Evaluate Adaptive Capacity and Resilience: Assess the existing coping mechanisms and resilience strategies in each region, such as water conservation practices, drought-resistant crop adoption, or governmental aid. The study examines how these factors contribute to each region's overall ability to withstand drought conditions and sustain economic stability.
- Support Policy Development: With detailed insights at the NUTS 3 level, the study provides a basis for creating policies tailored to regional needs. Recommendations might include region-specific drought preparedness plans, investment in irrigation infrastructure, or incentives for sustainable water use.

This study contributes directly to the objectives of the JRC PESETA and COACCH projects by providing valuable insights into regional climate change impacts. This study aligns with the PESETA project's focus on assessing sectoral vulnerabilities, particularly water scarcity and agricultural productivity, as critical consequences of drought. It highlights the localized effects of climate change, which complement PESETA's EU-wide assessments, offering data that can refine regional and sectoral risk evaluations.

Additionally, the study case contributes to the COACCH project by quantifying the socio-economic costs of drought, such as economic losses in agriculture or the costs of water resource management. This aligns with COACCH's aim of providing actionable and high-resolution assessments that stakeholders can use to design targeted adaptation strategies. Any recommendations for mitigating drought impact in the study case strengthen COACCH's framework for addressing the broader economic and social challenges posed by climate change in Europe.

Application of the methodology framework

Table 2 Application of conceptual framework for case study 2 - figure 1

Step 1: Climate and socioeconomic scenarios	
Climate scenario	Scenarios: RCP 4.5 / SSP2 and RCP 8.5 / SSP5 Year: 2030, 2050, 2100
Downscaled projections	Climate projections (air temperature, precipitation): downscaled projections for drought STL areas and identified CCHs (inputs from WP1). Socio economic projections: Using the EPIC (Environmental Policy Integrated Climate) and BIOMAT

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	(Biophysical Modelling and Analysis Tool) models.
Socioeconomic scenario (if relevant) For example: Economic activities, Social activities and/or other land-use projections for the local case study.	The socioeconomic scenario will include an analysis of how drought impacts various economic and social activities, as well as projections for land use changes. Agriculture: drought leads to reduced crop yields, livestock losses, and higher costs for irrigation. Economic losses in agriculture can lead to income instability, particularly in rural areas dependent on farming. Livelihoods are at risk, especially for farmers with limited access to drought-resistant crops or water-saving technologies. Agricultural Land Use: prolonged droughts may lead to shifts in land use, with farmers adopting drought-tolerant crops or shifting to less water-intensive forms of agriculture. Some areas may transition to non-agricultural uses if farming becomes unsustainable. Urbanization: In some regions, increasing pressure on urban infrastructure due to rural-to-urban migration may accelerate urban sprawl, changing the landscape and increasing water demand in cities. Ecosystem Changes: drought can cause land degradation and affect ecosystems, potentially leading to desertification, loss of biodiversity, and changes in land cover as vegetation struggles to survive.

Step 2: Spatial data integration	
Description	Will be integrated multiple sources of data: climatic data (temperature, precipitation, evapotranspiration from remote sensing, etc),

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	hydrological data (soil moisture in situ and from remote sensing), land use and vegetation data (satellite imagery or remote sensing data to assess land cover, vegetation health (NDVI), and changes in land use over time) and socio-economic data (agricultural, and economic data that provide information on population density, agricultural activity, and regional economic reliance on water resources) aggregated at NUTS3 level. By integrating climatic, hydrological, and socioeconomic data, geographic information systems (GIS) tools will be used to map drought severity, areas of vulnerability, and regions at risk of economic losses or water shortages. Vulnerability mapping will be made by identifying high-risk regions based on spatial patterns of water availability, agricultural dependence, and socioeconomic characteristics.

Step 3: Impact assessment	
Description	Evaluation of the consequences of drought events on agriculture and food security, biodiversity, energy and water availability, from the environmental, economic and social point of view (using EPIC & BIOMAT models). This process will identify vulnerable sectors and regions, guiding strategies for mitigation, adaptation, and resilience-building in affected areas.

Step 4: Risk assessment	
Description	Estimation of the potential risk by linking the drought hazard and socio-economic vulnerability.

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	Vulnerability assessments help identify regions most at risk from droughts, particularly those where agricultural systems, ecosystems, and water supply systems are already stressed. These assessments will use GIS-based tools to map climate risk and socio-economic vulnerability. Key components will include: • hazard identification: analyzing climatic data to determine the frequency, duration, and intensity of droughts using indicators like precipitation deficits, soil moisture anomalies, and drought indices; • Vulnerability assessment: examining the susceptibility of affected systems, such as agricultural dependency on water, infrastructure resilience, and the adaptive capacity of communities; • Exposure analysis: identifying the populations, economic sectors, and ecosystems at risk due to their reliance on water resources and their proximity to drought-prone areas. By quantifying risk through these components, the assessment will help to prioritize regions and sectors requiring immediate intervention in the study area. It also informs the development of strategies to reduce vulnerability, such as water management policies, drought-resilient agricultural practices, and early warning systems. Will informs the decision making to reduce the

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	social, economic, and environmental impacts of future droughts.

Step 5: Adaptation options	
Description	Adaptation options will be designed and investigated based on close cooperation with stakeholders.

Step 6: Decision support	
Description	Qualitative and quantitative assessments of the impact of adaptation options.

#3 STORM

Event based storyline (STL)

Climate Risk Typology: The Climate Risk typology is an approach that enables the identification of cities and regions that share similar climate risk characteristics concerning the hazards they face, and their levels of exposure and vulnerability to these hazards.

Description of the case study typology: The climate risk typology of the case study area is characterized by very high exposure to coastal hazards, which are regularly occurring in the cities and regions located in this part of Europe. The location of cities, people, infrastructure and socio-economic activities near the sea increases the risk of coastal flooding substantially for these regions. Furthermore, many of the regions are characterized by relatively high population densities and high intensity transport- and critical infrastructure, such as road, rail and port infrastructure, which can be severely affected during flooding events. Socioeconomic indicators suggest that the regions are among some of the wealthier in Europe, which may positively impact their ability to recover from extreme events and adapt to future climate change impacts.

Approximately 80 different NUTS 3 regions with similar characteristics are identified. The regions are relatively small compared to other parts of Europe.

The regions are in Denmark, Northern coast of Germany, The Netherlands, Belgium and North-western part of France (Figure 13).

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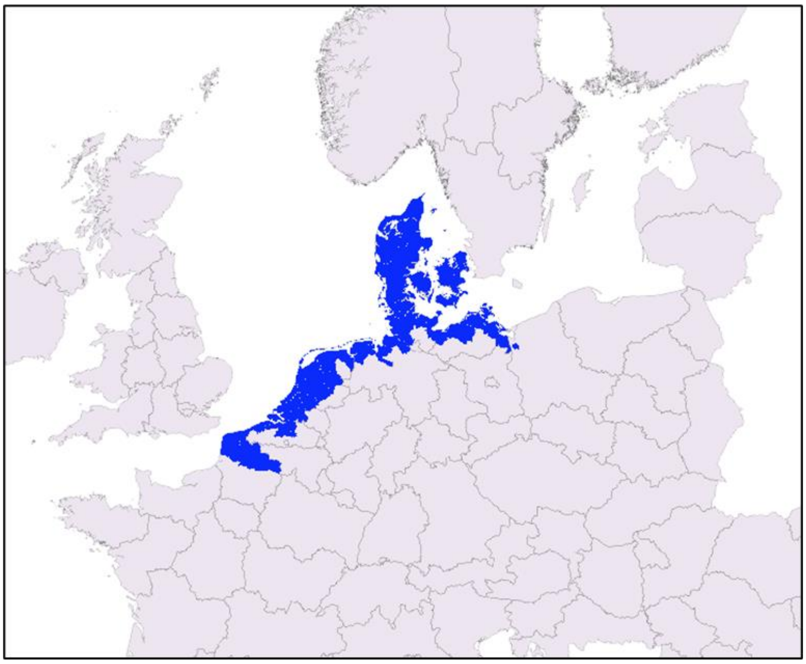

Figure 13: Storms, NUTS 3 regions with similar climate risk typology as the CSA3

<u>Event Description: Storm surge October 2023</u>

The regions of south-western Denmark and north-eastern Germany including many urban areas were severely affected by a major storm surge in late October 2023. Water levels during the event along with pictures illustrating some of the damages are presented below. The water levels observed during the storm correspond to return periods of more than 100 years for many of the locations (Figure 14).

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Figure 14: (A)Water levels and (B) images from the October 2023 storm surge

Climate Change hotspots (CCH)

The region of south-western Denmark and north-eastern Germany including the municipalities of Aabenraa and Haderslev in Denmark, and Flensburg and Kiel in Germany have been identified as CCHs for this case study (Figure 15).

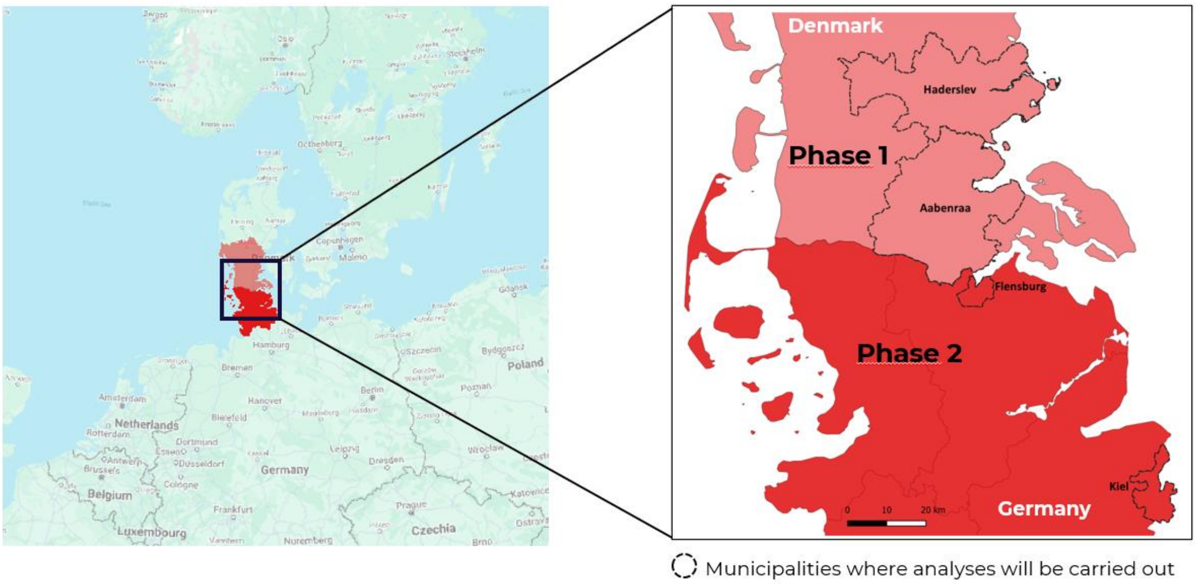

Figure 15: Map showing CCHs

The Climate Change Hotspots (CCH) are highly exposed and vulnerable towards the occurrences and impacts of storm surge from the Baltic Sea. The regions of Southwestern Denmark and Northern Germany has low lying coastlines, and cities in this region are often positioned in the bottom of fjords, next to the sea. The combination of a low-lying coastline with a high degree of human and economic activities next to the sea makes this region particularly exposed and vulnerable to the occurrences and consequences of flooding during storm surges. The region has experienced serious flooding events in the last decades, and most recently in October 2023.

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The EU green transition plans and national policies include a large expansion of existing large harbours and offshore renewable energy infrastructure, which could be at risk in the case of storms. The region has already experienced many severe flooding events in the past decades and will in the future be even more exposed to such events as sea levels are expected to rise as consequence of future climate change.

Decision makers and private investors in the region are in the process of planning for future infrastructure and economic development, including disaster risk management, and adaptation, and there is extensive stakeholder engagement already included in this process. The focus of decision makers is now to prepare and adapt settlements, infrastructure and activities to the rising threat of future storm surges.

Objective of this case study

The objective of this case study is to investigate the impacts of flooding events on land use including buildings, business, agriculture, infrastructure, transport, health, tourism, ecosystems, and historical/cultural values. The analyses will be conducted on a detailed geographical level for storm surges. An assessment of damage costs and risks of flooding events will be used as input to decision-making on adaptation measures. To support this, an open-source digital GIS data system for land use and flooding risks will be established.

Case studies on the socio-economic consequences of coastal flooding will be conducted for Aabenraa and Haderslev in Denmark (phase 1), and for Flensburg and Kiel in Germany (phase 2). Aabenraa and Haderslev municipalities are collaborating with us in the CROSSEU project with a particular focus on damages to infrastructure such as the harbour area. A similar collaboration will be proposed for the phase 2 cases of Flensburg and Kiel.

The case study will be based on detailed local digitalized GIS information to explore storm risks in relation to context specific assets and sectors including buildings, industry, harbour- and energy infrastructure, cultural/historical values, health, transportation, tourism, and ecosystems in a joint process with local stakeholders as inputs to a decision-making framework for adaptation. The DTU DamageCost model (Halsnæs et al., 2022, 2023) will be used and further developed to assess key inputs to adaptation decision making as part of the DSS. The model includes object-based damage cost functions based on statistical damage cost data, detailed income loss estimates related to transportation, tourism, and health supplemented with assessments of the value of recreational values and special ecosystems.

The results from the case study will be compared with the results from the COACCH and PESETAS projects at regional level, and this comparison will

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also be a main element in the upscaling to sectoral level based on regional analogies in Europe. The damage cost model is updated here with geographical activity-based information drawing, EUROSTAT NUTS3 information and CORINE land use data. The sectoral upscaling is drawn on data on the economic turnover of sectors which could be exposed to similar climate events around Europe.

The DTU DamageCost Model will be applied for the quantitative assessment of the socioeconomic consequences of floods. Based on the observations from the flooding in October 2023 the model will be further developed together with the stakeholders to better encompass damages to infrastructure. The sectors included in the current version of the DTU DamageCost Model is presented in the figure below (Figure 16).

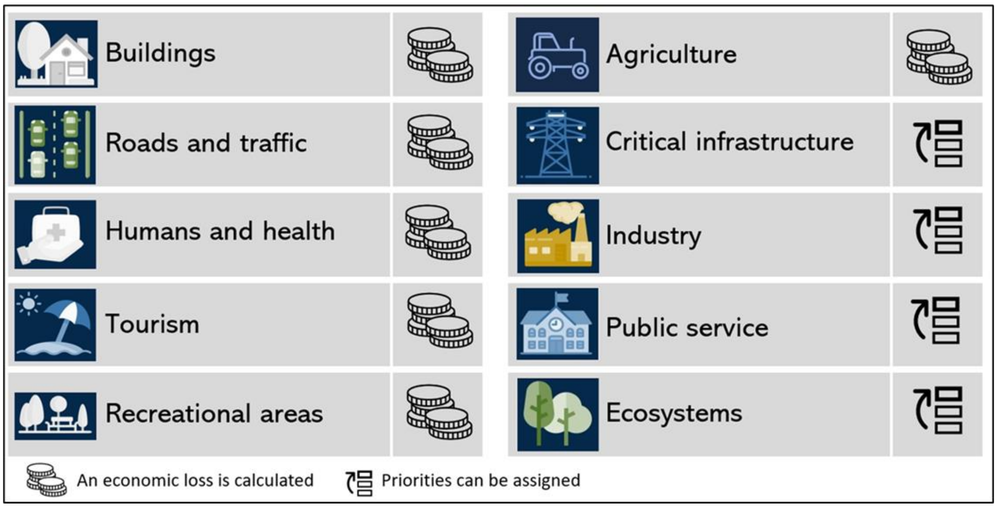

Figure 16: Sectors in DTU DamageCost Model

Application of the methodology framework

Table 3: Application of conceptual framework for case study 3 - figure 1

Step 1: Climate and socioeconomic scenarios	
Climate scenario	Scenarios: RCP 4.5 and RCP 8.5; SSP1-2.6, SSP2-4.5 and SSP3-7.0 Year: 2050, 2100, 2125
Downscaled projections	Projections of sea level rise for SSP scenarios are added to present-day storm surge statistics Example of data from Denmark Meteorological Institute (DMI) ClimateAtlas.

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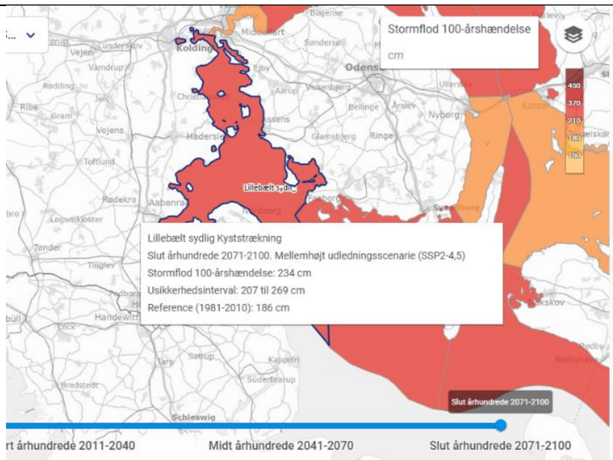
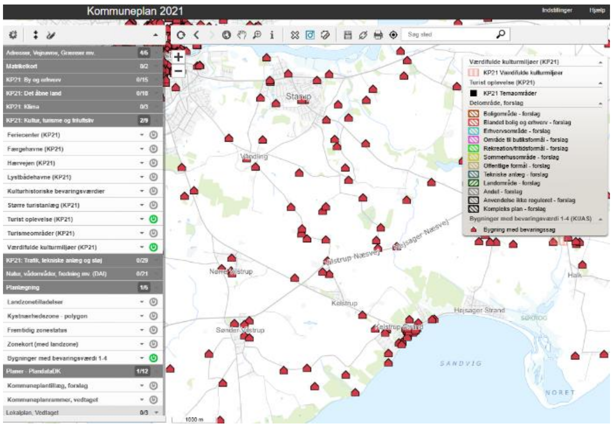
	
Socioeconomic scenario (if relevant) For example: Economic activities, Social activities and/or Other land-use projections for the local case study.	Urban development scenarios based on urban plans Link: [urban plans for Haderslev] Screenshot of digital municipal development plan for Haderslev. 

Step 2: Spatial data integration	
Description	Detailed land use data is overlayed with flood model at detailed spatial level 0.4 * 0.4 m

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Step 3: Impact assessment	
Description	Damages will be measured as flooding costs for all the sectors included in the Damage cost model, see figure above. The model applies the method of overlay analyses of the hazard data with the asset data (buildings, roads etc.) to identify those assets that are exposed to flooding and provides a quantitative assessment of the potential economic loss. This is a common approach when conducting impact assessment at the local scale, and one that is also used in other open source and commercial software such as Saferplaces or Scalgo Live.

Step 4: Risk assessment	
Description	Damage costs of flooding scenarios are multiplied with the likelihood of flooding events based on climate scenarios and high-water statistics for the case study areas

Step 5: Adaptation options	
Description	Adaptation options are selected based on dialogues with the stakeholders and municipal plans

Step 6: Decision support	
Description	Assessment of the damage cost will be useful for DSS in WP3

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#4 FLOOD

Event based storyline (STL)

North-eastern Italy is an area with high flood vulnerability, which is likely to be exacerbated by climate change. The local population is exposed to the risk of serious socio-economic consequences from these natural events. Historical records show that they often resulted in fatalities, homelessness, damaged buildings and interrupted road traffic. Local authorities are still debating with the community what possible risk mitigating options to undertake and information about public preferences for alternative mitigation and adaption options is crucial to design risk mitigation policies capable of generating high social benefits.

Event Description: The Vaia Storm

The Vaia storm impacted the Eastern Italian Alps between October 27th and the evening of October 29th 2018. The event occurred at the end of a climatic anomaly of prolonged drought. The synoptic situation was characterized by a trough, which deepened over the eastern Atlantic developing a wide cyclonic area at the surface of the western Mediterranean and moved towards north-western Italy. The storm dropped large precipitation amounts ranging from 200 to 500 mm over the mountains of the Eastern Italian Alps. In many places, the total accumulated precipitation was the highest ever recorded for a flood event lasting 3 days, with a rainstorm severity exceeding 300 yrs return time for the event cumulated precipitation (Giovannini et al., 2021). The event triggered debris flows and flash floods (Brenna et al., 2023) and led to 11 casualties.


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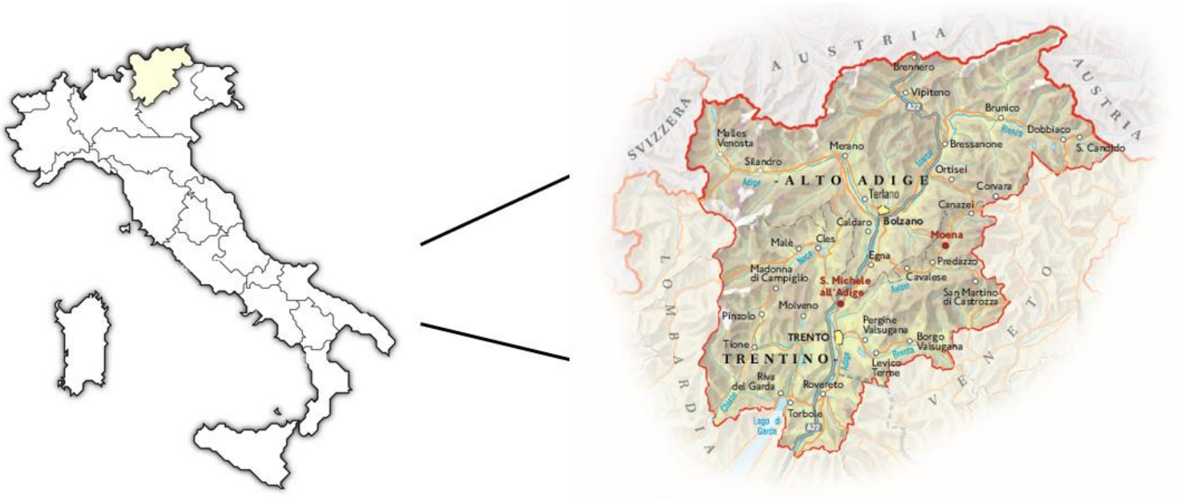

Figure 17: Impacts of the Vaia storm (upper part), Trentino Alto Adige map (lower part)

Climate Change hotspots (CCH)

Valley areas of the Trentino Alto Adige region (see map in Figure 17).

Reason for choosing the CCH

The area is characterised by high rise of sub daily precipitation extremes, as identified by Libertino et al. (2019) and Dallan et al. (2022), which, under appropriate hydrologic and hydrogeomorphic conditions, translate to increases in debris flows and flash flood activity. Additionally, firsthand experience based on multidecadal research work together with local institutions and stakeholders.

Objective of this case study

The objectives of the case study are to:

- assess the magnitude and frequency of current and future impacts and of their plausibility;
- monetize the benefits that M&A strategies could provide to society in alternative impact scenarios;
- explore how the social benefits of M&A strategies vary across different shares of the population.

To this end, we will use to model convection permitting climate models to quantify flood impacts on:

1. Residential areas;
2. Productive areas;
3. Roads
4. Touristic infrastructures
5. Agricultural land use

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This will allow us to address flood impacts in several key sectors, such as transport, agriculture and tourism.

Secondly, a Choice Experiment (CE) will address a large and representative sample of citizens (at least 2,000). The CE will be embedded in a survey administered via the web, also collecting additional information about respondents (attitudinal traits, socio-demographics). The econometric analysis (choice modeling) of collected data will allow us to estimate the total economic value (expressed in terms of willingness to pay) of the social benefits of the above alternative mitigation and adaptation strategies under different future impact scenarios. Tailored models (Latent class models) will be employed to assess how such benefits vary across different shares of the population (e.g., gender dimension). This approach will enable the assessment of potential inequality issues. Finally, the survey will include questions aimed specifically at addressing how Covid and geopolitical issues impacted household income, potentially reducing resources available for private flood protection. The survey will be shared with sectoral stakeholders and refined according to their feedback, in line with COACCH's focus on co-designing methods for assessing the socio-economic impacts of climate change.

Our modelling of flooding impacts and quantification of the associated socio-economic losses will complement the analysis of river flooding carried out within the PESETA project, by providing information at regional scale. Furthermore, in alignment with PESETA, we will investigate impacts in several key sectors, such as agriculture.

In line with COACCH's objectives, the estimation of the social benefits of adaptation strategies will allow to inform the design of policies that can be used by relevant stakeholders, including those involved in the case study.

Application of the Methodology Framework

Table 4 Application of conceptual framework for case study 4 - figure 1

Step 1: Climate and socioeconomic scenarios	
Climate scenario	Scenarios: RCP 8.5 Three 10-years time slices: 1996-2005; 2041-2050, 2090-2099.
Downscaled projections	Convection-permitting models from the CORDEX Flagship Pilot Project on Convective Phenomena over Europe and the Mediterranean for near and far future. The multi-

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	model ensemble is remapped on a common grid (3.02 km) over the study area.
Socioeconomic scenarios	Based on development plans of local/regional authorities of the Trentino Alto Adige region

Step 2: Spatial data integration	
Description	Climate and socio-economic data aggregated at least at the NUTS3 level

Step 3: Impact assessment	
Description	Use of available hydrological models to transform precipitation forcing into flood hydrographs. Use of new design floods to quantify impacts on: • Residential areas; • Productive areas; • Roads • Touristic infrastructures • Agricultural land use Estimation of monetary losses caused by the above impacts (in terms of loss of social benefits) via a Choice Experiment (CE), embedded in a survey addressing a sample of 2,000 citizens

Step 4: Risk assessment	
Description	Exposure and hazard data to estimate proxy for risk assessment Monetary assessment of risk based on CE results

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Step 5: Adaptation options	
Description	Quantification of prevented damage with different degrees of torrential works maintenance (via analytical simulation) Monetization of avoided damage (computed via analytical simulation) with different adaptation options from CE results

Step 6: Decision support	
Description	Quantitative assessment of flood impacts and benefits of adaptation options

#5 SNOW

Event based storylines (STL)

The European Climate Risk Typology framework provides background information about the dominant hazards and risk typology categories aggregated at the NUTS3 level for the two selected European mountain regions (Alps and Carpathians). Accordingly, there are 32 NUTS3 regions (out of a total of 54) in the Alps and 92 NUTS3 regions (out of 105) in the Carpathians with similar characteristics. In the Alps, these regions are subject mainly to the "landlocked and elevated" climate risk category, which is associated with the Alpine and central European mountains and uplands. These regions show a particularly high exposure of people, settlements and transport infrastructure to landslides (the key hazard) and fluvial flooding (the secondary hazard). The complex topography and projected increase in heavy precipitation are the main drivers explaining the large spatial distribution and exposure to these hazards across the Alps. These NUTS3 regions are projected to experience increasing migration in the future, although they have relatively high levels of adaptive capacity and gross domestic product (GDP). In the Carpathians, most NUTS3 regions are attributed to the "inland hinterlands" category, which overlaps vast parts of the Eastern Europe and central France . These regions are exposed to multiple hazards, including fluvial flooding, landslides, rising

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temperatures, heat waves and wildfires. The key hazards for these regions are fluvial flooding and landslides. These regions show a higher exposure of people, settlements and transport infrastructure to fluvial flooding than to landslides. These regions show lower GDP levels and employment opportunities.

In the CROSSEU project, the focus of CS#5 is on snow-related hazards, particularly snow avalanches, that are attributable to the NUTS3 areas with a complex topography and large fresh snow accumulations in the cold season. These hazards can produce fatalities, and damage to tourists and further people (i.e., huts, alpine refugees, tourist trails) and roads (i.e., high altitude roads), infrastructures and forest areas across both mountain regions. Winter tourism is a prominent socioeconomic activity in both mountain regions, which historically interfered with avalanche activity. Different entities monitor snow avalanches across the two mountain regions.

Despite the observed climate change, the avalanche activity and associated risk were found to vary considerably across the European Alps and Carpathian Mountains, with no clear systematic causal relationship (Stoffel and Huggel, 2012). A recent review on the climate change impacts on snow avalanche activity and related risks (Eckert et al., 2024) shows that the number and size of avalanches have declined at low elevations and that the share of wet avalanches has increased, even in high winter (typically from December to February across the Northern Hemisphere). Changes in snow properties driven by a warming climate were found to influence avalanche typology, as aligned with the physical understanding of avalanche activity under a warming climate (Bellair et al., 2017), with a shift towards powder cloud occurrences in cold weather conditions and more frequent wet avalanches in warmer weather. However, factors beyond climate change such as socioeconomic shifts, land use changes interacting with the topography and prevailing climate conditions, also play a significant role in the snow avalanche risk. Quantifying the individual impact of each factor remains a challenge, adding complexity to understanding and managing the snow avalanche risk in the long term.

Description of snow avalanche storyline events

In the framework of the snow hazard case study, multiple storylines (STL) have been identified associated with exceptional snow avalanche events occurring across the European Alps and the Carpathian Mountains (Figure 18). All the selected STLs produced meaningful effects at the local or regional scales and for all the target sectors including tourism (through the number of fatalities, burials, injuries and affected tourist infrastructure), forestry (damages in forest areas, wood losses) and transport (affected roads, and railways). The selected STLs were documented through a set of newspaper or media highlights (over the years) and are all relevant from

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the perspective of civil protection management measures that have been defined after most snow avalanche events. The selected snow avalanche STLs are studied for both mountain regions through (i) the analysis of the weather pre-conditions, (ii) documentation of damages, costs and socioeconomic effects at the NUTS3 level of each event (iii) selection of relevant snow hazard indicators for climate change hotspot (CCH) identification and analysis, (iv) identification of sectoral elements at risk, (v) selection of hazard indicators for estimating the snow avalanche hazard potential at NUTS3 level in the present and future climate (different scenarios), and (vi) definition of a set of integrated (sectoral) indicators for estimation of the snow avalanche risk under climate change. The expected key outcomes of this case study including the hazard and risk estimation data for the two mountain regions (NUTS3 level) will be used to feed the CROSSEU decision-support system.

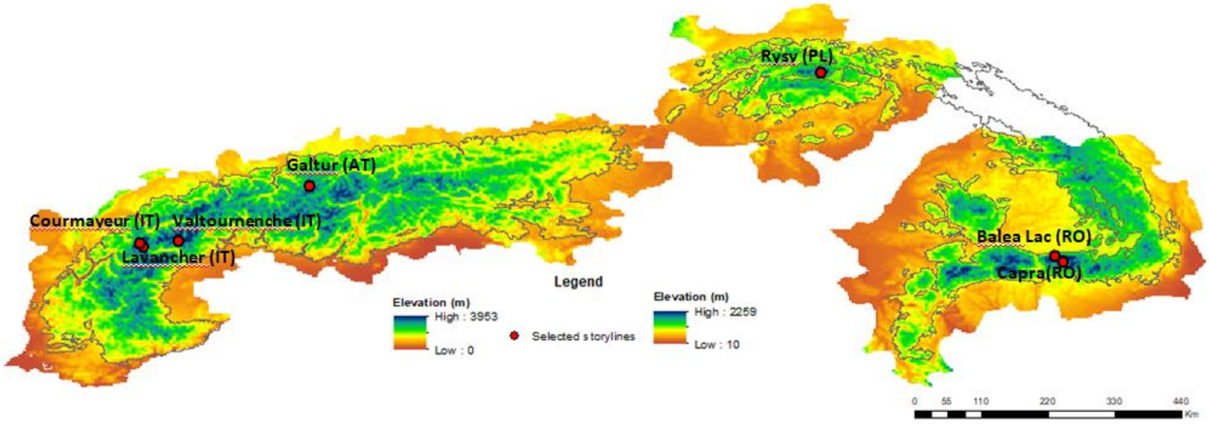

Figure 18: Spatial distribution of the selected snow avalanche STLs in the European Alps and Carpathian Mountains

Climate Change hotspots (CCH)

Attribution studies indicate that the European Alps are emergent fragile and vulnerable environments to the present-day and future climate change (Kotlarski et al., 2023), with many areas experiencing rapid glacier retreats (Sommer et al., 2020) and changes in snow cover duration and snow avalanche typology (Matiu et al., 2021, Olefs et al., 2020). Furthermore, the main responses to climate warming observed in the Carpathian Mountains refer to early spring snow melting episodes, declines in the snow cover duration (Micu et al., 2020, 2015) and in some areas, changes in snow avalanche activity (Voiculescu et al., 2017).

The selected STL events for the hotspots are briefly described hereafter:

STL1 – the Courmayeur events (Valle d'Aosta – 2,600 inhabitants, the Italian Alps). To assess the socio-economic impacts of snow avalanches, the case study will also analyze other recent events that occurred in this specific

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location, including those on February 3, 2019 (4 deaths), December 18, 2022 (1 death), and March 19, 2023 (2 deaths).

STL2 – the Valtournenche events (Valle d'Aosta – 2,300 inhabitants, the Italian Alps). To assess the socio-economic impacts of snow avalanches, the case study will also analyze other recent events that occurred in the Valtournanche municipality, including the events of 15 December 2019 (1 death), 29 November 2021 (1 death) and 14 March 2023 (1 death)

STL3 – the Lavanchers event (March 1, 2010 – Valle d'Aosta – 87 inhabitants, Italian Alps). The snow avalanche event of March 1, 2010, in Lavancher, exhibits certain peculiarities that raise new questions about the management of avalanche-prone areas that intersect with inhabited areas and infrastructure. In the face of these challenges, scientific research, technological innovation, and territorial management strategies must evolve in the coming years towards innovative solutions and choices

STL4 – the Galtur event (February 23, 1999 – Galtur – 867 inhabitants, the Austrian Alps). The Galtur event has claimed many lives (31 people were killed, 26 tourists and 5 locals) and caused extensive damage to properties, with small and close-knit community structures destroyed (National Geographic, 2013). This event is recognized as "the most lethal snowstorm recorded" (Traynor, 1999) and determined the rezoning of the former "green snow avalanche risk zone" that is today higher

STL5 – the Balea Lac event (April 17, 1977 – Sibiu county, the Romanian Carpathians, the northern slope of the Făgăraș Mountains). On April 17, 1977, it was registered the most catastrophic snow avalanche in Romanian history, which resulted in the tragic loss of 23 lives in the Balea glacial cirque (Voiculescu, 2009) a ski Winter School, four adults and 19 high-school children (aged 15–18) were caught by an avalanche while exercising on the slope. This snow avalanche event is the most prominent tragedy for the Romanian Carpathians due to the impressive death toll.

STL6 – the Capra chalet event (February 02, 2023 – Argeș county, the Romanian Carpathians, the southern slope of the Făgăraș Mountains). On February 02, 2023, a group of tourists (60 persons) were isolated by a large snow avalanche that blocked the road DN7C, between 106-107 kilometres and damaged the Capra chalet and the parked. A mixed rescue operation team (including civil protection representatives, mountain rescuers) evacuated the tourists and part of the chalet employees in two days. The road DN7C was closed at the time of year (from October to March). This snow avalanche event is a relevant example of the consequences of non-compliance with the road closure regulation imposed by the local authorities.

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STL7 – the Rysy event (January 28, 2003 – the Nowotarski region – the Polish Carpathians, Tatra Mountains). This snow avalanche was selected due to the high number of recorded fatalities (9), including high school and university students a group leader and the large rescue operation efforts.

Previous evaluations centered on the identification of the areas prone to certain hazards (i.e., avalanches, droughts, earthquakes, extreme temperatures, floods, forest fires, landslides, storm surges, tsunamis, volcanic eruptions, winter and tropical storms), hazard patterns or clusters have been conducted in the framework of the ESPON Hazard project show that avalanche hazard is prevalent in the European mountain regions popular for winter sports, but the specific risks vary widely. Most avalanche cases used in this evaluation were triggered by human activities, particularly in areas with high tourism, challenging the collection of reliable data on avalanche risk in less frequented mountain regions of Europe. As a result, the ESPON snow avalanche hazard evaluation may overestimate the risk in some areas with lower mountains and less snow, especially those without extensive tourism. The avalanche hazard mapping at the European level indicates the Carpathian Mountains and especially the European Alps include vast areas (NUTS3) with high and very high levels of snow avalanche hazard (Figure 19). These areas have reported high frequency of snow avalanches, as derived from several sources (i.e., ESPON Database 2012; European Avalanche Warning Service; Neve e Valanghe reports). The selected STLs in the CROSSEU project overlap NUTS3 areas with high or very high snow avalanche hazard levels.

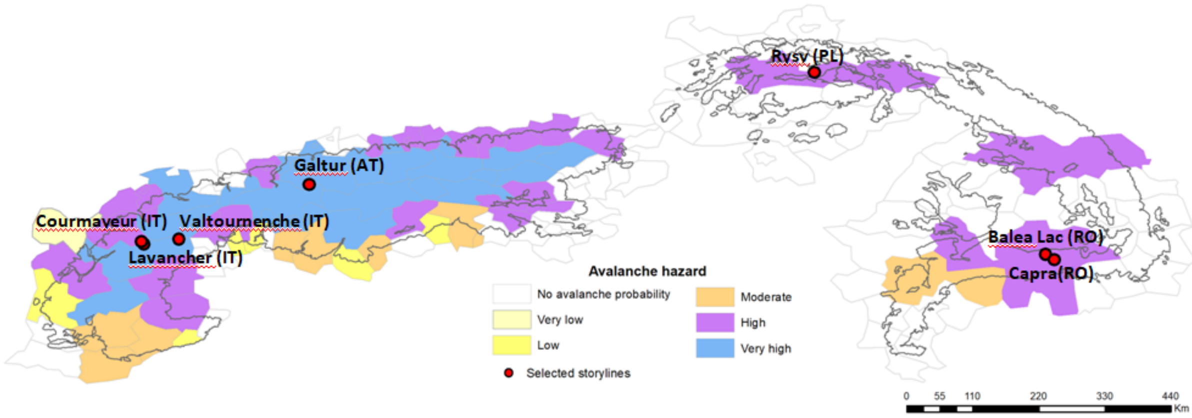

Figure 19: Snow avalanche hazard

Objective of the study

This case study aims to assess the impacts of climate change on snow avalanche activity and its expected consequences for mountain communities and key sectors like tourism, forestry, and transportation at the NUTS3 level. Steps towards establishing an upscaling framework of the

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snow avalanche risk under different climate scenarios are also foreseen in this case study. The analyses will be conducted from both mountain regions following a common methodological framework between the two mountain regions that includes: (i) identification of snow avalanche storylines from both mountain regions and documentation of their impacts, based on the investigation of various available sources (i.e., avalanche inventories, press releases, event factsheets or reports), (ii) analysis of the snow hazard relevant for the snow avalanche activity, including the exploration of the preparing/triggering weather conditions, evaluation of the terrain susceptibility, selection relevant snow hazard indicators, estimation and mapping of snow avalanche hazard, (iii) identification and analysis of climate change hotspots, derived from background seasonal climate change signals (i.e., air temperature, precipitation, snow depth, wind) and changes in climate hazard indicators relevant for the snow avalanche activity (i.e., number of days with snow depth over 30 cm, maximum number of consecutive snow cover days). Some snow-related hazard indicators (i.e., frequency of rain-on-snow events) will be computed using the outputs of state-of-the-art physically-based models (i.e., SNOWPACK, SNOW-17), (iv) analysis of socio-economic vulnerability to snow avalanches (NUTS3 level) and (v) development of a set of integrated risk indicators (IRIs) for snow avalanche, reflecting the synergy between climate hazard, decision-making (available policy) and impact based on relevant climate indicators of snow avalanche pre-conditions, civil and environmental risk indicators under different RCPs and SSPs. IRIs will be used to estimate the future change in the snow avalanche potential under different climate scenarios.

The case study results will be extrapolated to European regions with comparable climatic, topographic, and socio-economic conditions. This upscaling process will integrate stakeholder input on sector-specific vulnerabilities and socio-economic data to estimate potential impacts on tourism, forestry, and transportation. The upscaled results will be used in the decision support system to inform decision-making and snow avalanche management strategies in the long term.

Application of the methodology framework

The analyses conducted in this case study target three sensitive sectors to snow hazards (tourism, forestry, transport) and the NUTS3 level.

Table 5: Application of conceptual framework for case study 5 - figure 1

Step 1: Climate and socioeconomic scenarios

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Climate scenario	Scenarios: RCP 4.5 / SSP2 and RCP 8.5 / SSP5; Years: 2030, 2050, 2100
Climate projections and downscaling	Climate projections of air temperature, precipitation, snow depth, snowfall water equivalent, wind speed; downscaled projections for snow avalanche STL areas and identified CCHs (inputs from WP1)
Socioeconomic scenarios	Land cover and land use (inputs from WP1)
Step 2. Spatial data integration	
Description	Climate and socio-economic data (i.e., population density, age dependency ratio, GDP per capita, poverty level, income inequality, housing density, density of roads and railways) from both the European Alps and Carpathian Mountains regions aggregated at the NUTS3 level
Step 3. Impact assessment	
Description	Estimation of the impact of the changing climate (present-day and future climate) on the snow avalanche potential and target sectors (tourism, forestry, transport)
Step 4. Risk assessment	
Description	Estimation of the potential risk by linking climate hazard and socio-economic vulnerability. Cost estimations of the potential impacts will be made with sectoral stakeholders
Step 5. Adaptation options	
Description	Adaptation options will be selected through dialogues with the stakeholders and risk management plans
Step 6. Decision support	
Description	Qualitative and quantitative assessments of the impact of adaptation options. This analysis will

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	consider risk reduction and damage metrics, changes in fatality statistics from STL areas due to implementation of preventive measures. It will also integrate stakeholder feedback on the perceived effectiveness and acceptability of implemented measures and estimations of their ecological implications, local community preparedness and awareness and how adaptation options are integrated in the broader risk management framework.

The CROSSEU project focuses on snow hazards, specifically snow avalanches, in two major European mountain ranges, the Alps and the Carpathians. Despite being significant winter hazards with high potential for severe damage, these hazards are currently underexplored in the context of EU climate resilience. The objectives of case study #5 align closely with those of the COACCH and PESETA projects, contributing to a broader understanding of sectoral and regional climate change vulnerabilities addressed by both initiatives. The CROSSEU project builds on the methodological approaches of COACCH and PESETA, leveraging stakeholder engagement results and incorporating socio-economic impact analyses to support adaptation planning via the DSS. Case study #5 shares COACCH's emphasis on collaborative approaches for co-designing and assessing the socio-economic impacts of climate change. Key connections include: (i) Integrating stakeholder needs to co-design the DSS and develop snow avalanche risk mitigation strategies for the mid- and long-term, (ii) Evaluating potential economic impacts under various climate scenarios, (iii) Developing policy recommendations to support climate adaptation efforts. The linkages with PESETA are centered on the focus on sector-specific impacts of climate change. These connections are illustrated through: (i) Assessing regional (Alps and Carpathians) and local (NUTS3) vulnerabilities to climate-related hazards, (ii) Estimating socio-economic impacts of snow avalanches on various sectors, including tourism, forestry, and transport, as well as on local communities, (iii) Providing evidence-based policy recommendations to inform risk management and adaptation strategies. Through these linkages, case study #5 integrates methodologies and findings from both COACCH and PESETA, contributing to informed decision-making and enhanced climate resilience.

#6 INDIRECT

Event based storyline

"Shifting Climate Seasonality and Water Availability: Risks for Socio-Ecological Systems in the Lower Danube (LD)," revolves around the

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profound challenges that climate change imposes on the Lower Danube region (Figure 20). This region is defined by an extensive floodplain that spans approximately 6,000 km², housing crucial ecosystems, agriculture, energy infrastructure, and human settlements.

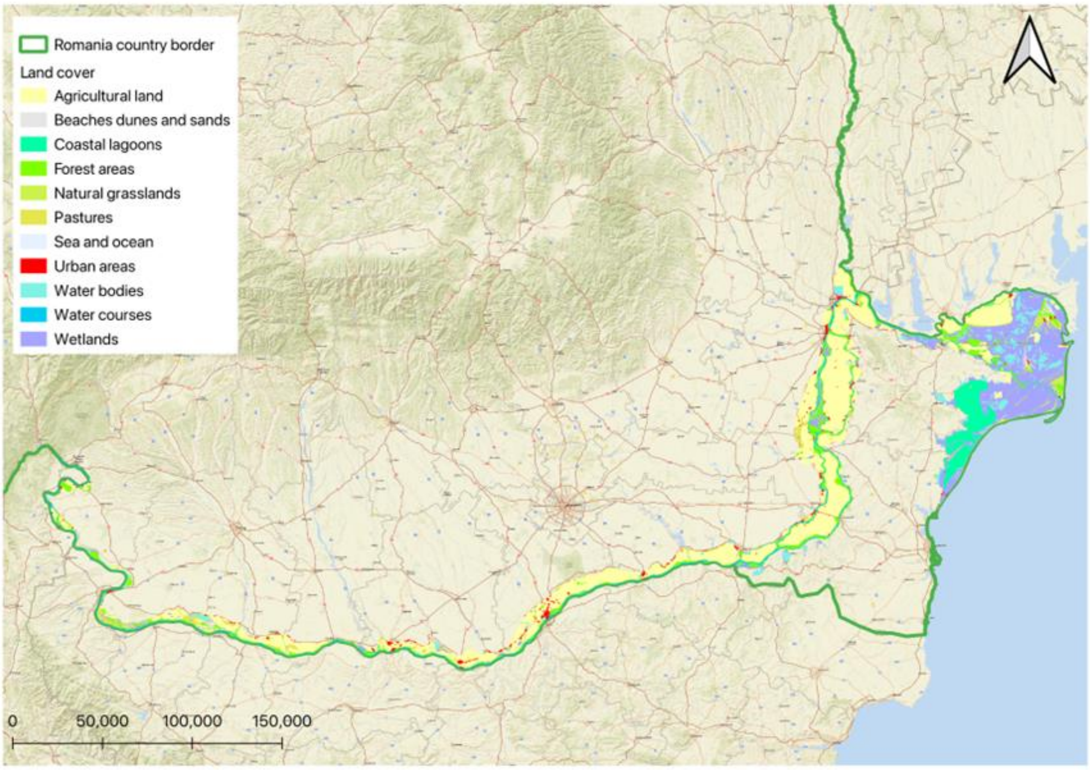

Figure 20: Case study area - Lower Danube (land cover)

<u>Description of the case study climate risk typology:</u>

The European Climate Risk Typology framework provisions the background information about the dominant hazards and risk typology categories aggregated at NUTS3 level for the Lower Danube region. In the LD most NUTS3 regions are attributed to the "inland hinterlands" and "southern lands" category (Figure 21). These typology classes are characterized by hot and dry conditions, which are projected to worsen with climate change. The Lower Danube Floodplain faces increasing exposure to hazards such, coastal threats, rising temperatures, heatwaves, wildfires, and fluvial flooding. High soil moisture stress and rising water consumption for agriculture heighten the risk of water shortages and drought. Also, these regions experience higher-than-average poverty levels, lower GDP, and limited infrastructure, all of which increase vulnerability to climate risks. The combined impact of these socio-economic and environmental factors contributes to greater overall climate risk in these regions.

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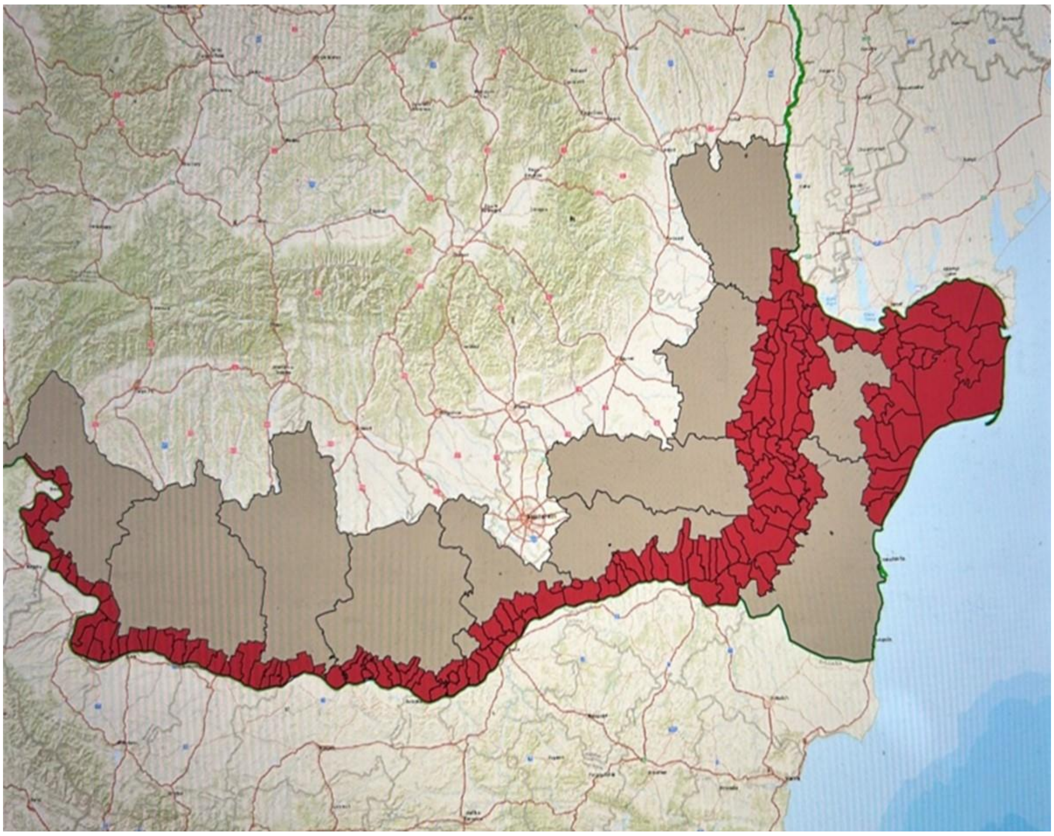

Figure 21: Hotspots identification NUTs 3 level and localities in the Lower Danube

In the last decades, in the LD have been noticed changes in timing, duration, and variability of seasonal events like flood pulse due diminished snowpack and early season melting in the Danube basin, earlier spring thaw and later fall frost, early-summer or late-fall heatwave events, changes in the solid and liquid precipitation phases (including the occurrence of rain-on-snow events), as well as disturbances of the duration of the convection season trigger. This shifting of the climate seasonality has immediate consequences, but also triggers slow onset multi-hazard risks on the socio-ecological systems. Changes in seasonality can have adverse effects on ecosystems, such as altering the plant phenology phases or mis-alignments between species that may rely on one another, and can generate behavioural changes related to the use of labour in agriculture and fluvial transport.

Event description:

The Lower Danube region has been significantly affected by climate change, leading to shifting climate seasonality and altered water availability. This area is characterized by extensive floodplains that support vital ecosystems, agriculture, and human settlements. Recent climate patterns have revealed a trend of increasing droughts and floods, notably in 2003, 2012, and 2015, which have severely impacted agricultural

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productivity and water resources. The drought in 2012 prompted the EU to provide over €2.4 million in compensation to Romania for agricultural and economic damage, with reports indicating that 40% of corn production was destroyed due to the drought, highlighting the significant effects of these climate events. In 2015, the government supplemented the budget of the Ministry of Environment, Waters, and Forests with 483.407 € from the intervention fund to address the impacts of drought in the Danube Delta.

Figure 22: Severe drought from July and August 2022 on the Danube River, where the water level reached one of its lowest points in the last century.

Flooding events have also been catastrophic, with the 2006 flood affecting 1,100 km^2 and causing damages valued at €340 million. Additional flooding in 2010 impacted 38 km^2, while in 2014, 100 hectares were flooded in localities such as Pristol, Gârla Mare and Salcia.

Figure 23: Severely damaged home in Rast, Dolj County, after the 2006 flooding

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Figure 24: Surlari-Dorobanțu dyke during the major flooding of April 2006.

Climate Change hotspots (CCH)

The Lower Danube region is identified as a Climate Change Hotspot (CCH) due to the synergic impact of drought and land cover changes in the area that are hindering navigation on the Danube, the wetland extend and functioning leading to biodiversity change (decline), affecting different ecosystems services (human wellbeing) (production capacity, decline in C sequestration capacity, leisure activities and fishing).

Wetlands will be the most affected ecosystems due to climate change in different climate change scenarios (Segan, et al 2016).

Reason for choosing this CCH:
The Climate Change Hotspot (CCH) in the Lower Danube region is highly exposed and vulnerable to the combined impacts of severe drought and land cover changes. This area features extensive wetlands and agricultural lands along the Danube River, which are vital to the local economy and biodiversity. The combination of a sensitive ecosystem, significant agricultural activities, and reliance on the Danube for transportation and irrigation makes this region particularly susceptible to climate-related extremes. Prolonged droughts and shrinking wetland areas have led to notable biodiversity decline and reduced agricultural productivity. In recent decades, the Lower Danube has faced worsening drought conditions.

Objective of the study

The objective of this study is to assess the risks posed by shifting climate seasonality and water availability in the Lower Danube region. This includes investigating the socio-ecological impacts of climate extremes, such as droughts and floods, on agriculture, energy

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infrastructure, human settlements, and ecosystems. The study will use climate and socio-economic scenarios to develop adaptation strategies, incorporating tools like GIS for risk mapping and participatory approaches with local stakeholders. The outcomes will support decision-making processes for building climate resilience, particularly focusing on water management, agriculture, energy sectors and naval transport.

Application of the methodological framework

The framework is designed to develop a comprehensive resilience strategy for the Lower Danube region, addressing the critical impacts of climate change on water availability, agriculture, energy, and socio-ecological systems. Central to this strategy is the integration of a participatory modelling approach, actively involving a broad spectrum of stakeholders from various sectors, including agriculture, energy, water management, healthcare, and urban development. Through collaborative engagement, local communities, farmers, energy companies, and policymakers will co-develop climate adaptation strategies tailored to the unique challenges of the region.

At the heart of the framework are climate projections based on RCP 4.5 and RCP 8.5 scenarios, that will allow us to assess the dynamics of temperature and precipitation, focusing on the anticipated impacts for 2030, 2050, and 2100. These projections will be complemented by socio-economic scenarios, assessing how economic activities, urban development, and agricultural practices will adapt to changing climatic conditions. The use of geographical mapping through GIS systems will be crucial in identifying areas most vulnerable to climate extremes, providing detailed insights into land use changes, and identifying major risks to agriculture, urban settlements, and ecosystems.
These models will further explore how key sectors such as agriculture, energy, biodiversity, and infrastructure are affected by climate change. For instance, agriculture in the region will face significant challenges due to shifting water availability, while energy infrastructure, particularly hydropower, may struggle during droughts. The Danube's fluctuating water levels will disrupt navigation, affecting trade and transportation, and increasing health risks from heatwaves, vector-borne diseases and diseases correlated with limited access to water. To better understand these dynamics, tools like Fuzzy Cognitive Mapping (FCM) will be employed, allowing stakeholders to visualize the relationships between climate drivers and the supply of ecosystem services under different climate scenarios.

Incorporating a human dimension is vital, as climate change disproportionately affects the livelihoods and infrastructure of local

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communities. We will analyse the livelihood dependence on climate-sensitive sectors such as agriculture, fishing, and tourism, and assess poverty and income levels to understand the vulnerability of lower-income households, who often have fewer resources for adaptation. Furthermore, we will evaluate communities' access to infrastructure and services like healthcare, water supply, and early warning systems, recognizing that inadequate infrastructure limits their ability to respond to climate events. Education and awareness levels will also be measured to assess the adaptive capacity of local populations.

To quantify these vulnerabilities, we will integrate the Climate Vulnerability Index (CVI), a tool designed to assess the overall susceptibility of communities, ecosystems, and regions to climate risks. The CVI will draw on multiple indicators, such as heatwave duration, Danube discharge, mortality rates, and energy production levels, providing a comprehensive view of how vulnerable the region is to climate change and how prepared it is to adapt. Data for these indices will be sourced from institutions like the National Institute of Statistics, with ongoing efforts to acquire relevant datasets.

A risk assessment will focus on both direct and indirect impacts across multiple systems, with particular attention to agriculture, energy, navigation, and health. Direct impacts will include the reduction in agricultural productivity due to drought and the strain on energy infrastructure from fluctuating river water levels. Indirect impacts will consider broader socio-economic consequences, such as the increase in health risks from climate-related diseases and the potential displacement of populations from flood-prone areas. Decision Support Systems (DSS), incorporating GIS platforms and cost-benefit analysis tools, will help policymakers make informed choices about the most effective adaptation strategies. These systems will ensure that adaptation measures are sustainable and aligned with community needs, with regular stakeholder consultations and focus groups.

We will emphasize long-term sustainability, providing a model for other climate-sensitive regions across Europe. By focusing on a multi-sectoral approach—encompassing agriculture, energy, water management, healthcare, and urban development—it seeks to foster resilience at both the local and regional levels. This integrated, data-driven approach will enable decision-makers to address the complex challenges posed by climate change, ensuring the future sustainability and well-being of the Lower Danube's socio-ecological systems.
The framework will be used to develop a resilience strategy for the Lower Danube region, focusing on how climate change affects water availability, agriculture, and socio-ecological systems. It integrates a participatory modelling approach that actively involves stakeholders

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across multiple sectors—agriculture, energy, water management, healthcare, and urban development. These stakeholders, including local communities, farmers, energy companies, and policymakers, will collaborate to co-develop climate adaptation strategies.
In line with the project COACCH approach, our case study is relying on stakeholders to co-design the methods for assessing the socio-economic impacts of climate change.

Table 6: Application of conceptual framework for case study 6 - figure 1

Step 1: Climate and socioeconomic scenarios	
Climate scenario	Scenarios: RCP 4.5 and RCP 8.5 Year: 2030, 2050, 2100
Downscaled projections	Downscaled projections for the Lower Danube region are based on regional climate models (RCMs) derived from global climate model (GCM) outputs under RCP4.5 and RCP8.5 scenarios. These projections include detailed assessments of changes in temperature, precipitation, and extreme weather events such as floods and droughts, providing high-resolution insights into seasonal and annual river discharge patterns.
Socioeconomic scenario (if relevant) For example: Economic activities, Social activities and/or other land-use projections for the local case study.	These projections will be complemented by socio-economic scenarios, assessing how economic activities (energy production, naval transportation), health (vector-bone disease) and agricultural practices will adapt to changing climatic conditions. Use of geographical mapping through GIS systems will be crucial in identifying areas most vulnerable to climate extremes, providing detailed insights into land use changes, and forecasting risks to agriculture and ecosystems.

Step 2: Spatial data integration	
Description	Climate and socio-economic (agricultural production, energy production- Cernavoda and Iron Gates, transport, number of vector-borne disease cases) data from Lower Danube

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	floodplain (Romania) regions aggregated at the NUTS3 level.

Step 3: Impact assessment	
Description	Assess the multiple impacts on the socio-ecological systems determined by the shifting climate seasonality, diminished water availability and increasing occurrence of extreme events.

Step 4: Risk assessment	
Description	Estimation of the potential risk by linking climate hazard and socio-economic vulnerability. The CROSSEU project aims to evaluate the impacts of diminished water availability in the context of climate change, focusing on the agriculture, energy, health and transportation sectors. To achieve this, we will involve relevant stakeholders from the case study area to: (a) identify the key challenges related to diminished water availability and (b)co-design, develop and test the CROSSEU Decision management

Step 5: Adaptation options	
Description	Adaptation options for the Lower Danube region are developed through discussions with stakeholders to identify priorities and co-create risk management plans that address regional vulnerabilities. These include measures to mitigate flood and drought risks.

Step 6: Decision support	
Description	Decision support for the Lower Danube is provided through a tailored multi-criteria framework that incorporates economic, environmental, and social

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	considerations to guide adaptation strategies. Co-developed with stakeholders, this participatory framework ensures the relevance and applicability of measures by incorporating local knowledge and priorities. The approach integrates with the broader CROSSEU DSS, facilitating consistent monitoring and effective implementation of climate adaptation strategies in the region.

#7 INDIRECT

Event based storyline (STL)

The Climate Risk Typology is a method that allows for the identification of cities and regions with similar climate risk profiles. This includes assessing the types of hazards they face, as well as their levels of exposure and vulnerability. For instance, the European Climate Risk Typology (European Climate Risk Typology, n.d.) provides a comprehensive framework for categorizing and comparing these risks across different regions in Europe.

Description of case study typology

The climate risk typology of the case study area is characterized by high exposure of the energy system to concurrent climate hazards such as heatwaves, droughts, and storms. These hazards frequently impact regions in France, particularly those with high shares of renewable energy, including hydropower, solar, and wind energy. France is chosen as the starting point as having the stakeholder EDF (Électricité de France) involved as partner in the project. The core of this typology is defined by the vulnerability of energy infrastructure, combined with rising energy demands, especially related to cooling, and environmental stressors.

France, with its significant renewable energy investments led by EDF, faces substantial operational challenges during extreme weather events. Regions with high population densities and intensive energy demands are particularly vulnerable. Socioeconomic indicators suggest that these regions, while relatively wealthy, require substantial investments in adaptation and resilience measures to mitigate the adverse effects of climate hazards on energy security.

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Many regions in France are identified with similar characteristics, spread across especially southern and central parts of the country, already experiencing and predicted to experience even more frequent heatwaves, droughts, and exposure to storms impacting renewable energy infrastructure.

Event description

Heatwave and Drought - Summer 2022

Many regions of Southern and Central France, experienced severe heatwaves and droughts in the summer of 2022 (Figure 25). These events led to record high temperatures and prolonged dry periods, significantly impacting the energy systems in these regions. Data and observations indicate that temperatures reached record highs for many stations, maximum temperatures were above 45°C, and precipitation levels were at a historic low. The heatwave strained the energy infrastructure, increasing demand for cooling while reducing the efficiency of thermal and nuclear power plants due to higher temperatures affecting cooling water. Together with increased demand this greatly increased the operational stress on the energy grid (Copernicus, 2022).

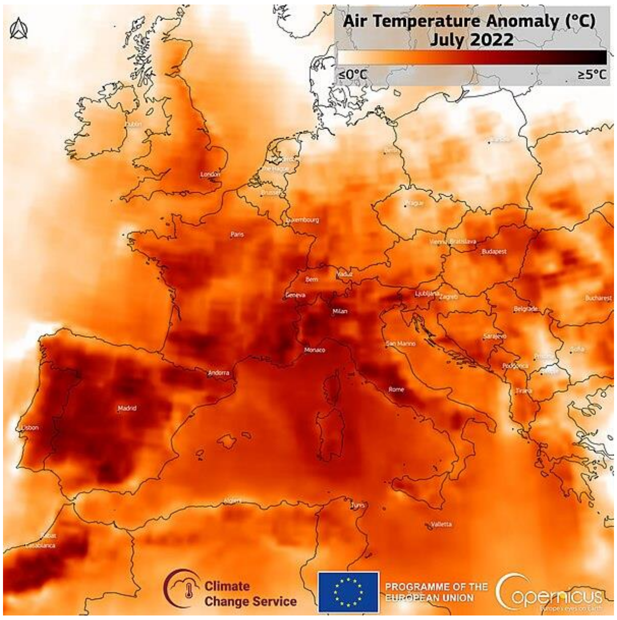

Figure 25: July 2022 saw intense, prolonged heatwaves, breaking temperature records worldwide. It was one of the three warmest Julys globally and the sixth warmest in Europe. The image shows June 2022 temperature anomalies, with peaks of +4°C in Italy, France, and Spain. Source: CCCS.

Storms - Autumn 2021 (Storm Aurore)

In the October of 2021, Central France, including the regions of Auvergne-Rhône-Alpes and Bourgogne-Franche-Comté, faced a server storm that

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caused extensive damage to solar and wind energy installations. Wind speeds exceeded 175 km/h in the town of Fecamp, and disrupted energy production and transmission leaving 250.000 people without electricity (Fance24, 2021). The storm further impacted other western and central European countries such as England, The Netherlands and Germany.

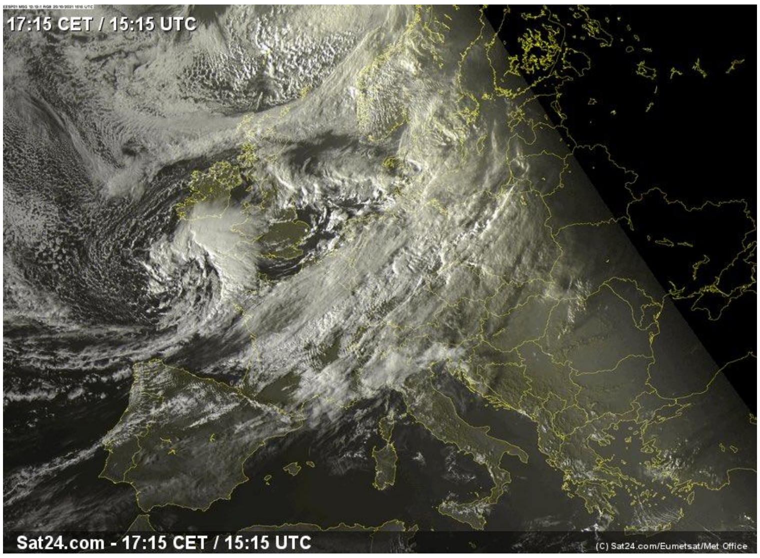

Figure 26: Satellite image showing storm Aurore approaching North Western France. Image credit: EUMETSAT, Sat24

Climate Change hotspots (CCH)

The case study will have a focus on the energy sector in France due to the high involvement of EDF in the project acting as a stakeholder for CS7. This also means that the events investigated will be focusing on France. However, it is planned that all the requested energy variables will be calculated for a domain covering all of Europe and aggregated on different NUTS levels starting at national. This will allow for a wider range of stakeholders from the energy sector from different countries to benefit from the outputs of the project on a longer term. Figure 27 below shows a general example of The Teal tool which will be used for visualization and access point for retrieval of the aggregated data.

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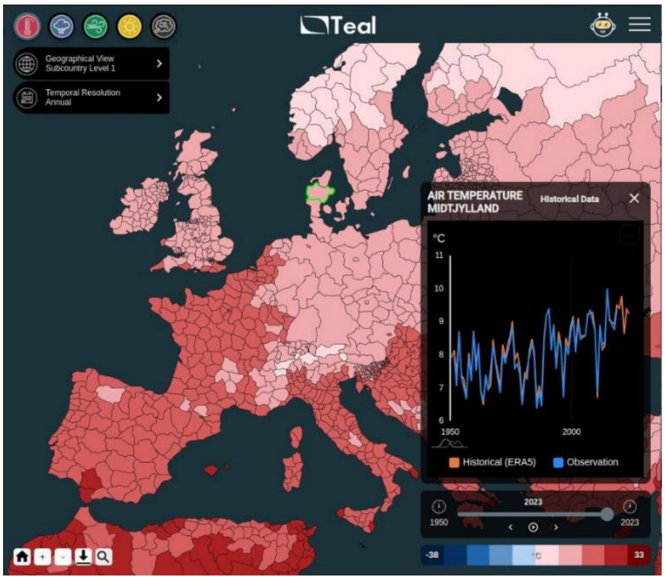

Figure 27: Example from the current public Teal Tool version that will be tailored to fit the needs of EDF acting as end-user.

Objectives of the study

This case study aims to assess the implications of heatwaves, droughts, and storms on energy demand and security within Europe, focusing on renewable-dominated systems such as wind, solar, and hydropower. The objective is to explore impacts on electricity demand, generation reliability, and cooling needs under different climate and emission scenarios. Specific focus will be on the operational costs, adaptation requirements, and investment needs to maintain energy security amid increasing renewable energy integration. The analysis will include an exploration of the trade-offs between mitigation and adaptation strategies (M&A) in energy supply and their impacts on consumer behaviour, as well as the indirect impacts on consumer responses amid recent and ongoing energy crises. Policy adaptation needs will also be developed collaboratively with sector stakeholders based on the outcomes.

Application of the methodological framework:

Table 7: Application of conceptual framework for case study 7 - figure 1

Step 1: Climate and socioeconomic scenarios	
Climate/socioeconomic scenarios	We will consider different Shared Socioeconomic Pathways (SSPs)—specifically SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5—to account for uncertainties in future climate projections.

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Energy Systems	The analysis will focus on renewable energy systems, including wind, solar, and hydropower, which are susceptible to extreme climate events like heatwaves, droughts, and storms.
Years	The time horizons for the study are set at 2050, 2070, and 2100.

Step 2: Spatial and temporal data integration	
Description	Climate data will be downscaled temporally to an hourly resolution to capture peak load and demand fluctuations in energy grids. Spatial downscaling will align with the ERA5 data resolution of 0.25° x 0.25°. The downscaling methods will be tailored to each specific variable to ensure accuracy.

Step 3: Impact assessment	
Description	The Plan4EU model will simulate scenarios incorporating extreme climate conditions to assess their impact on energy systems. Key focus areas include electricity demand shifts, generation reliability challenges, and increased cooling needs under varying climate and emission scenarios. Relative Deviation of the following variables will be assessed, considering a case with « average" "climate" scenarios and a case where the set of climate scenarios also includes extreme scenarios: Average Operation cost for a selected year, Average and maximum level of non-served electricity, Marginal costs peak/average

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	marginal cost and Investment cost to ensure an adequate level of non-served energy

Step 4: Risk assessment	
Description	Risks will be evaluated by comparing different climate and socioeconomic scenarios against a baseline. The assessment will identify vulnerabilities in renewable energy infrastructure due to climate stresses, such as reduced hydropower availability during droughts and damage to wind and solar installations from storms.

Step 5: Adaptation options	
Description	The study will identify necessary system reinforcements, including investments in renewable generation capacity, energy storage solutions, and cooling infrastructure. Flexibility options like demand response programs and load shifting will be explored to manage peak demand without significantly increasing emissions. Possibly, technological adaptations and the incorporation of storage systems will be evaluated for their effectiveness in mitigating climate impacts.

Step 6: Decision support	
Description	Economic analyses will quantify the benefits and costs of each adaptation strategy, focusing on variables such as

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	operational costs, investment requirements, and energy security metrics. The results will guide policymakers and stakeholders, like EDF, in making informed decisions about adaptation strategies.

The Plan4EU model (openENTRANCE, 2021), developed under the H2020 project Plan4res, is used to simulate scenarios that include extreme climate conditions—particularly high temperatures and drought affecting renewable energy systems in Europe. Climate conditions are represented across different time horizons (2050, 2070, and 2100) and emission pathways (ssp126, ssp245, ssp370, ssp585), based on high-resolution data from selected CMIP6 models. First step that has already been implemented and tested on a single model has been a downscaling of the temporal dimension down to an hourly resolution, which is important when looking at peak load and demand conditions to energy grids. Furthermore, the data is also downscaled to a common spatial resolution consistent with ERA5 data (0.25x0.25 degrees). The downscaling method has been chosen depending on the variable.

Four primary analyses will be performed:

Scenario Feasibility Assessment: Examining the feasibility of various renewable generation mixes, including evaluations of the demand-supply dynamics under different socio-economic conditions and levels of renewable penetration.

Investment and Reinforcement Needs: Identifying system reinforcement requirements, including investments in renewable generation, energy storage, and cooling infrastructure, to address increased demand and reduced hydropower availability due to drought.

Flexibility and Load Management: Exploring flexibility options such as demand response and load shifting, particularly in residential sectors, to manage summer cooling peaks without substantial increases in emissions.

Risk Assessment for Renewables: Evaluating risks specific to renewable infrastructure under climate stresses and the role of adaptation options like technological adjustments and storage systems in mitigating these impacts.

Additionally, the assessment incorporates secondary factors, including potential migration-induced demand surges and irrigation demands

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impacting water resources. Results from the plan4EU simulations will be used to model energy system adaptation needs and inform planning for renewable energy security.

The COACCH and PESETA projects have significantly advanced the understanding of climate change impacts on Europe's energy sector. COACCH has provided downscaled assessments of climate change costs across various sectors, including energy, emphasising stakeholder engagement to ensure practical relevance. Its analyses have highlighted the economic implications of climate-induced changes in energy demand and supply, particularly concerning renewable energy sources.

Similarly, the PESETA projects have evaluated climate change impacts on multiple sectors within the EU, with a focus on the energy sector. It has examined how temperature variations influence energy demand, especially in residential heating and cooling, and assessed the broader economic consequences of these changes.

Our study aligns with COACCH and PESETA by assessing climate hazards—heatwaves, droughts, and storms—on renewable energy systems but goes further in keyways. It focuses on Europe but also has a specific focus on France's energy infrastructure, enabling tailored adaptation strategies for regions with high renewable energy integration. Additionally, it incorporates extreme event simulations to evaluate resilience under compounded hazards, which is less emphasised in broader EU studies. Finally, our detailed economic assessment, including operational and investment analyses, offers actionable insights for stakeholders like EDF to maintain energy security amid rising renewable energy integration.

#8 SPILLOVER

Event based storyline (STL)

Climate Risk Typology: Climate change impacts on global agriculture

Climate change is expected to impact countries unevenly. While tropical regions are expected to be adversely affected by climate change, regions with temperate climates and those in the boreal north could potentially benefit from a moderate rise in temperatures. However, the overall effect is predicted to be unfavourable, with global crop yields expected to decline at around 1 percent per decade.

The uncertainty on the expected magnitude is also large. Projected impacts vary by crop, region, timeframe and RCP, depending on the current temperature level and degree of warming (Figure 28Figure 28).

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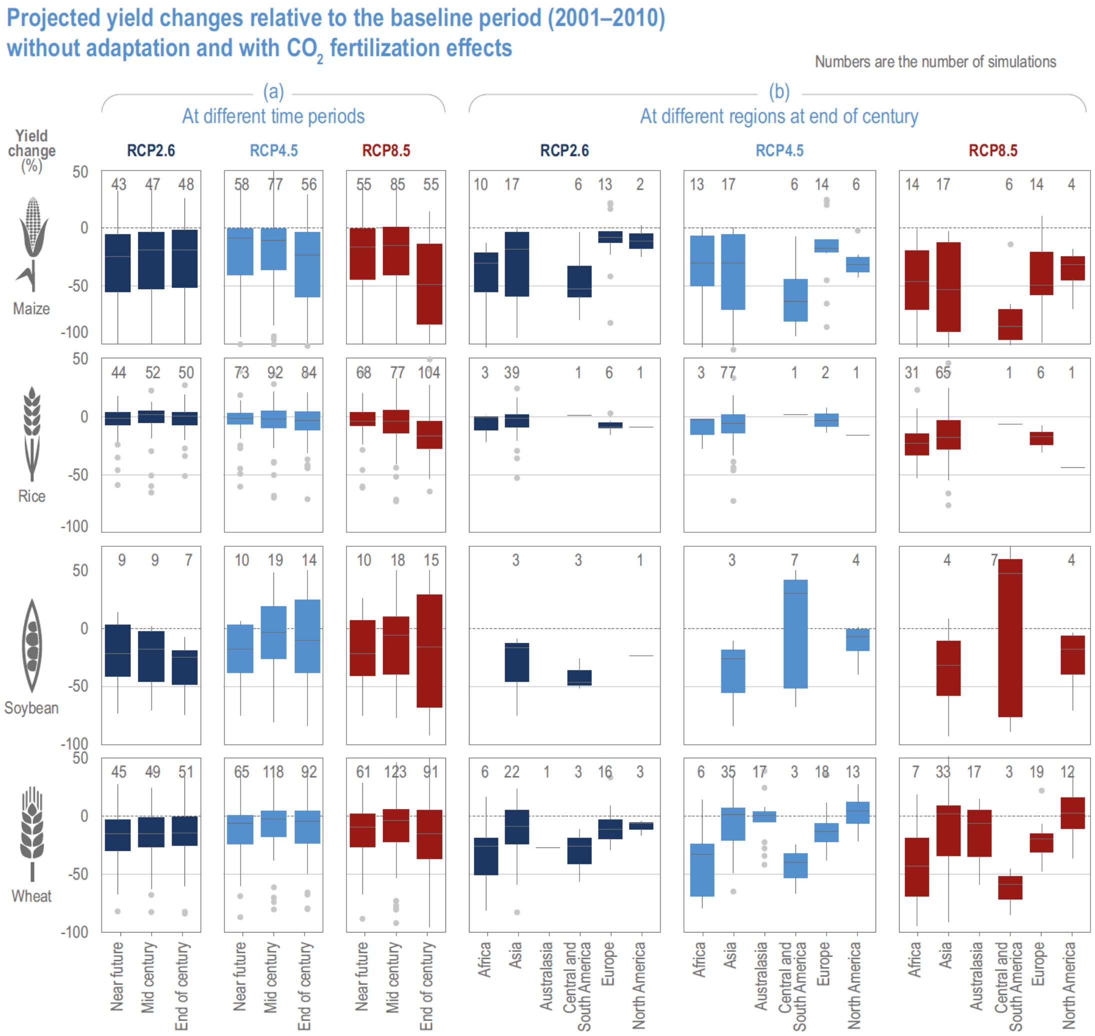

Figure 5.6 | Projected yield changes relative to the baseline period (2001–2010) without adaptation and with CO_2 fertilisation effects (Hasegawa et al., 2021b). The box is the interquartile range (IQR), and the middle line in the box represents the median. The upper and lower end of whiskers are median 1.5 × IQR ± median. Open circles are values outside the 1.5 × IQR. **(a)** At different time periods (near future, NF, baseline to 2039; mid-century, MC, 2040–2069; end-century, EC, 2070–2100) under three RCPs, and **(b)** at different regions at EC.

Figure 28: Projected yield changes Source: IPCC (2022)

Regions are not only affected by the direct impact of climate change on their agricultural yields, but they are also vulnerable to climate-induced changes in competitiveness. In fact, farmers in regions where climate change increases agricultural yields may produce more and experience greater access to markets, while farmers in regions adversely affected by climate change may lose their market share as they face lower yields and greater competition from elsewhere.

The graph below, taken from Calzadilla et al. (2015), shows that the climate change impacts on welfare and GDP vary widely across regions and climate change scenarios. The direct impact of yield changes resulting from climate change explains around 20 percent of the change in regional welfare (upper graph). However, the changes in the terms of trade induced

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by climate change, indirect impact, explain around 50 percent of the variation in regional welfare (lower graph).

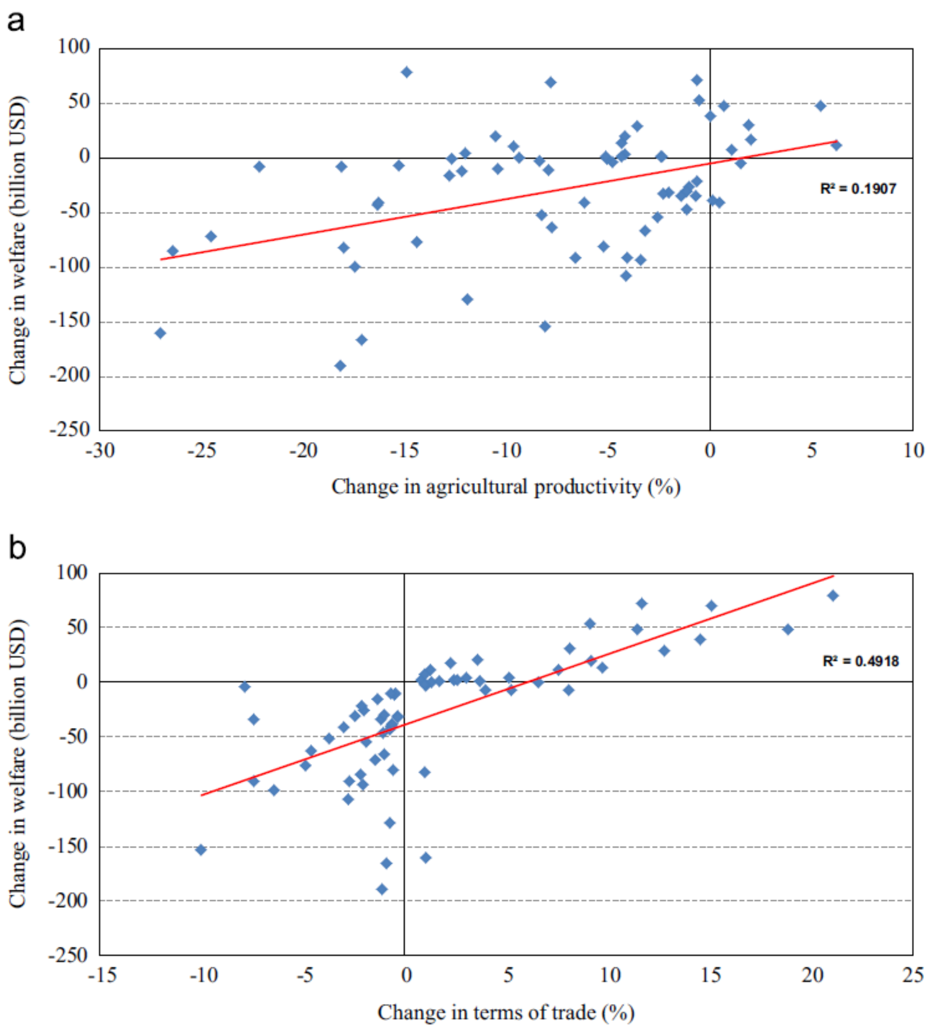

Fig. 4. Model outputs: impacts of climate change in 2050: change in welfare as a function of changes in agricultural productivity and the terms of trade. Note: each (*x*,*y*) pair contains information for a specific region and climate change scenario. (a) Agricultural productivity and (b) Terms of trade.

Figure 29: Climate change impacts on welfare and GDP. Source: Calzadilla et al. (2015).

Climate Change hotspots (CCH)

This case study examines climate change impacts on agriculture from a global perspective, with a specific focus on Europe at the NUTS2 level.

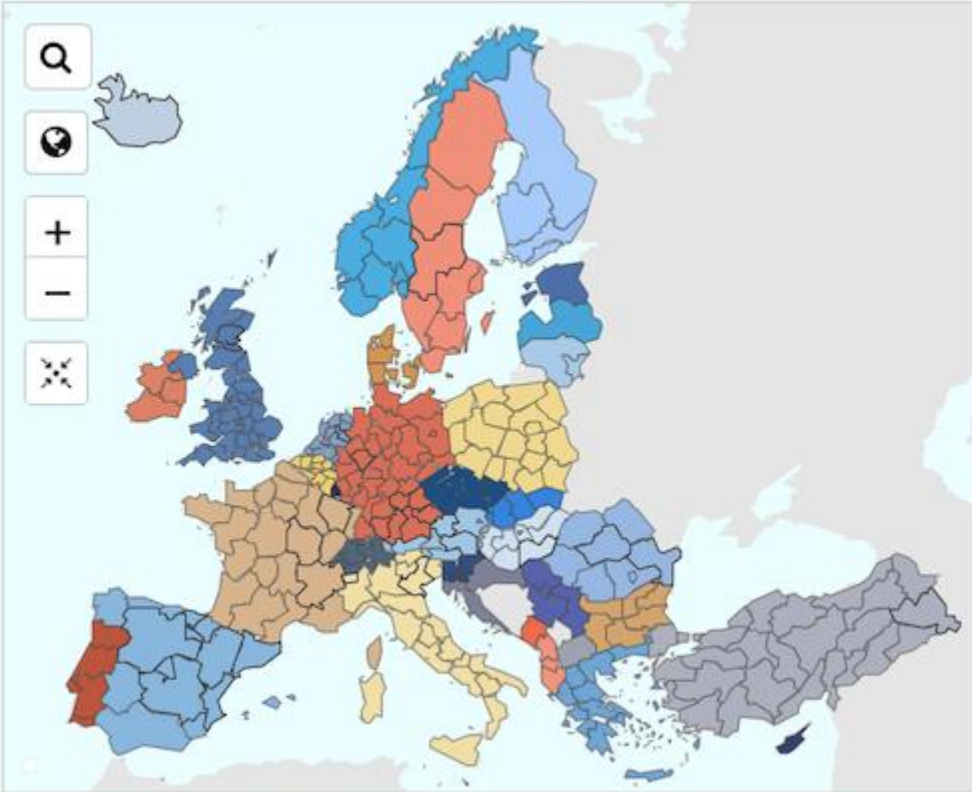

Figure 30: NUTS2 regions across Europe.

Source: Eurostat website

Reason for choosing the CCH

This case study conducts a global analysis of climate change impacts, rather than focusing on specific hotspots. It focuses on assessing climate change impacts on the agricultural sector and heat stress on labor productivity. An economy-wide and global analysis is essential to estimate spillover effects across sectors and across countries. The analysis aims to be conducted at the sub-national level to provide detailed regional insights in Europe.

Objective of this case study

The objective of this case study is to estimate the direct (changes in agricultural and labour productivity) and indirect (changes in competitiveness) impacts of climate change. Focusing on specific CROSSEU hotspots, it will assess transboundary effect associated linked to changes in trade patterns.

To do that, we are going to extend the UCL Environmental Global Applied General Equilibrium (ENGAGE) model to increase the geographical representation of European countries at the NUTS1/NUTS2 level (WP1). The development of the ENGAGE model builds on the methodological

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approaches of COACCH and PESETA, leveraging insights from spatial economic assessments and downscaling techniques to enhance the accuracy and relevance of climate impact evaluations. The 'sub-national ENGAGE' model will be used for the spillover analysis.

Application of the methodology framework

Table 8: Application of conceptual framework for case study 8 - figure 1

Step 1: Climate and socioeconomic scenarios	
Climate scenarios	Scenarios: We are going to consider different RCPs to account for uncertainty on future climate projections Crops: The analysis will focus on maize, rice, wheat and an aggregated sector comprising all other crops. Years: 2020, 2030, 2040, 2050. Results for 2100 are difficult to get as it involves predicting how the global economy will look like in 2100.
Socioeconomic scenarios	We are going to consider different SSP to account for uncertainty on future socioeconomic development.
Downscaled projections	We are going to downscale the economic results to NUTS3 levels using simple approaches.

Step 2: Spatial data integration	
Description	A consistency with other case studies is needed, especially those looking at the agricultural sector and heat stress (CS1, CS2 and CS6) The climate change scenarios need to be represented at the same geographical level than ENGAGE

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	The results from ENGAGE are expected to be downscaled at NUTS2 and NUTS3 level, depending on the CS.

Step 3: Impact assessment	
Description	ENGAGE, as an economy-wide global model, is capable of assessing impacts across sectors and regions, considering the economic interconnections among sectors throughout the supply chain. ENGAGE represents the production, consumption and trade of agricultural, industrial and services sectors with great detail.

Step 4: Risk assessment	
Description	The risk assessment is conducted by evaluating different scenarios and comparing them against a baseline scenario.

Step 5: Adaptation options	
Description	Some adaptation options could be considered, depending on the final model characteristics (e.g., if it considers irrigated and rainfed crops).

Step 6: Decision support	
Description	The economic benefits and costs of each adaptation strategy will be computed and captured by different economic variables (e.g GDP, trade). The change in these indicators will inform policymakers about the effectiveness of the adaptation strategies.

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5. Cross cutting consistency and comparison for upscaling

5.1 Cross-Cutting Consistency and upscaling

Cross-cutting consistency involves ensuring that the methodologies, data, and models used in localised case studies can be seamlessly integrated and applied to broader geographical and sectoral contexts. This requires a harmonized approach that considers the following factors:

- Standardised methodologies: Case studies will adopt standardized methodologies for data collection, analysis, and reporting. This ensures comparability across different studies and facilitates the integration of findings.
- Data harmonization: Data used in case studies should be harmonized in terms of spatial and temporal resolution, units of measurement, and data quality standards. This ensures that data from different sources can be seamlessly integrated and used for upscaling.
- Model compatibility: Models used in case studies should be compatible with upscaling to broader contexts. This requires careful consideration of model assumptions, parameterization, and sensitivity to changes in scale.
- Stakeholder engagement: Consistent stakeholder engagement is crucial throughout the upscaling process. This ensures that upscaled assessments remain relevant and responsive to the needs of different stakeholders across various sectors and regions.

Comparison for upscaling involves systematically comparing and analyzing findings from individual case studies to identify commonalities, differences, and cross-cutting themes. This comparative approach is essential for drawing broader conclusions and informing upscaling efforts. Key aspects of comparison for upscaling include:

- Identifying common patterns: Comparative analysis helps identify common patterns and trends across different case studies, providing insights into the generalizability of findings to broader contexts.
- Understanding contextual factors: Comparing case studies helps understand the influence of contextual factors on socio-economic risks and impacts. This allows for the development of upscaling strategies that are sensitive to regional and sectoral variations.
- Developing cross-cutting conclusions: Comparative analysis facilitates the development of cross-cutting conclusions that transcend individual case studies. These conclusions provide valuable insights for policymakers and stakeholders at broader scales.
- Informing upscaling methodologies: Comparing case studies can inform the development and refinement of upscaling methodologies. This includes identifying best practices for data harmonization, model compatibility, and stakeholder engagement.

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By emphasizing cross-cutting consistency and employing a comparative approach, CROSSEU ensures that its upscaling process is robust, reliable, and capable of generating insights that are relevant and applicable to diverse European contexts.

5.2 Upscaling Socio-Economic Assessments in CROSSEU: Bridging the Local and the European

Understanding the socio-economic implications of climate change is paramount for developing effective adaptation and mitigation strategies. While localized case studies provide valuable insights into specific contexts, the ability to upscale these findings to broader geographical and sectoral scales are crucial for developing comprehensive policy responses (Fünfgeld and Dahlmann, 2023). The CROSSEU project recognizes this imperative and incorporates a robust upscaling protocol within its methodological framework.

The upscaling process within the CROSSEU project aims to enhance resilience to climate change (CC) and extreme events by integrating results derived from STL and STL-CCH and ensuring their applicability and relevance at a European scale. This process involves synthesizing context-specific information and generating generalisable conclusions applicable across different regions, sectors, and stakeholder groups. CROSSEU's upscaling protocol is designed to ensure the transferability and generalizability of findings from localized case studies to wider European contexts.

5.2.1. Data Requirements and Harmonisation

Consistent and comparable datasets are fundamental for meaningful upscaling. To maintain the consistency between case studies and the upscaled outputs, it is essential to ensure the availability of datasets with a comparable spatial and temporal resolution across the whole EU in each STL. Each case study will review open data sources (such as EUROSTAT, Copernicus, and other European projects (e.g., COACCH and PESETAS)) to collect comparable datasets at the EU level.

5.2.2. Modelling Data

The outputs from detailed case studies will be integrated into a broader overview of risks and vulnerabilities. To achieve a comprehensive understanding, data from sectoral case studies will be utilised to cover larger regions within the STLs. Open data sources, such as EUROSTAT, Copernicus, and other European projects (e.g., COACCH and PESETAS), will play a crucial role in enriching the dataset.

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Sectoral models used in case studies are critically evaluated for their applicability at broader scales. Sensitivity analyses are conducted to identify and adjust critical parameters, ensuring that models remain accurate and reliable when applied to larger regions and sectors. Adjustments may be needed in parameters like aggregation levels for land use data, damage cost functions, and storm surge levels to improve the accuracy and reliability of models.

5.2.3. Upscaling Procedure

The upscaling procedure consists of three key elements:

STLs Development: A range of plausible scenarios is developed based on European sectoral studies, providing a comprehensive picture of potential outcomes for upscaled assessments. Stakeholder consultations are integral to this process, ensuring that scenarios are relevant and reflect diverse regional contexts.

Stakeholder Engagement: Engaging stakeholders from different sectors and regions is crucial for validating and refining upscaling scenarios. Workshops and consultations provide a platform for sharing preliminary findings and gathering feedback, ensuring that upscaled assessments are grounded in practical realities.

Comparative Analysis: A comparative approach is adopted to analyse findings from individual case studies, identifying commonalities, differences, and cross-cutting themes. This comparative analysis facilitates the development of comprehensive conclusions that can be generalized to broader contexts.

5.2.4. Integration of Quantitative and Qualitative Data

Both quantitative and qualitative data will be incorporated into the knowledge database. Ensuring a comprehensive and multifaceted approach to data integration will enhance the robustness and usability of the information.

Collaboration between WP1, WP2 and WP3 tasks will be essential to establish a robust knowledge data system. This system will support the integration and dissemination of both quantitative and qualitative data. Regular updates will be necessary to incorporate the latest data and insights, ensuring the system remains relevant and effective.

5.2.5. Barriers and Uncertainties

The upscaling process is not without its challenges. Uncertainties in data and models, discrepancies between localized and aggregate assessments,

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and the inherent complexity of socio-economic systems can pose barriers to accurate upscaling. CROSSEU acknowledges these challenges and incorporates strategies to mitigate them:

- Uncertainty Analysis: The project explicitly addresses uncertainties in data and models, employing sensitivity analyses and other techniques to quantify and communicate the level of confidence in upscaled assessments.
- Model Validation: The validity of upscaled models is rigorously tested by comparing their outputs with observed data and findings from other studies. This validation process ensures that models remain reliable when applied to broader contexts.
- Collaborative Approach: CROSSEU fosters collaboration among researchers, stakeholders, and policymakers across different sectors and regions. This collaborative approach facilitates knowledge sharing, data harmonization, and the development of upscaling strategies that are robust and widely applicable.

Upscaling socio-economic assessments is a critical component of the CROSSEU project, enabling the transfer of knowledge from localized case studies to broader European contexts. By adopting a systematic upscaling protocol, CROSSEU ensures the generalizability and policy relevance of its findings. The project's commitment to addressing uncertainties, validating models, and fostering collaboration further strengthens the robustness of its upscaling approach. The insights gained from this upscaling process will be instrumental in informing effective adaptation and mitigation strategies at regional, national, and European levels.

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6. Conclusion

In conclusion, this report has presented a harmonized methodological framework for assessing the socio-economic risks and impacts of climate change. The methodology is designed to be robust, consistent, and applicable across a range of geographical and sectoral contexts. The methodology incorporates a six-step approach that guides the assessment process, from scenario development and data integration to impact and risk assessment, adaptation options, and decision support tools. This structured approach facilitates consistency and comparability across different case studies, enabling the identification of cross-cutting themes and the development of broader conclusions.

The case study section provides detailed information about how the case studies have addressed the different analytical steps, and in this first reporting of the case study results, there is a particular focus on the development of STLs and CCHs. This provides a solid background for the more detailed assessment of impacts and risks of climate events in the different hotspots, which subsequently will be addressed in the case studies. A key area here will be to go more into detail about selecting impacts measures for costs and other socioeconomic impacts and to apply these in the individual case studies.

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