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D1.1 – Report on co-design and operationalisation of the CROSSEU methodology

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Executive summary

This deliverable presents the key components of the methodological framework of the CROSSEU project used for its operationalisation throughout the implementation period. It includes a synthesis the key findings of a comprehesive state-of-the-art analysis (SoA), that targeted the achievements, challenges, gaps, progress in modelling, co-design approaches and existing decision-support systems in the CROSSEU sectors. It also describes the modeling, upscalling and co-design protocols to be implemented in CROSSEU for a harmonised analysis of socio-economic risk and impacts of climate change, in relation to the guiding methodological principles of the project. An overview of stakeholder engagement activities until M6 (the first stakeholder engagement co-design workshops conducted at case study area and European levels).

Keywords

Climate change, case study areas, climate change hotspots, climate policy, climate resilience, decision support, cross-sectoral, climate change impact, stakeholder engagement, modelling frameworks, methodologies, protocols, socio-economic risks, upscalling

Abbreviations and acronyms

Acronyms, abbreviations	Full word
AI	Artificial Intelligence
AgMIP	Agricultural Model Intercomparison and Improvement Project
ARBM	Adaptive Resilience-Based management
BC-IAM	Benefit-Cost – Integrated Assessment Model
BGP	Biogeophysical
CC	Climate Change
CAP	Common Agricultural Policy
CCAP	Climate Change Action Plan
CGE	Computable General Equilibrium model
CCH	Climate Change Hotspot
CS	Case study
CSA	Case study area
DDM	Demographic Distribution Models
DICE	Dynamic Integrated Climate Economy
DSS	Decision Support System
EC	European Commission
ECA&D	European Climate Assessment and Dataset
ECB	European Central Bank
ECHO	European Climate and Health Organistation
ECMWF	European Centre for Medium-Range Weather
EDG	European Green Deal
EEA	European Environmental Agency
EIOPA	European Insurance and Occupational Pensions Authority's

	dashboard on the insurance protection gap for natural catastrophes
ENGAGE	Environmental Global Applied General Equilibrium model
ERDB	European Bank for Reconstruction and Development
FOLU	Food and Land Use Coalition
FUND	Climate Framework for Uncertainty, Negotiation, and Distribution
GDP	Gross Domestic Product
GHG	Green House Gases
GIS	Geographical Information System
IAM	Integrated Assessment Model
IGO	Intergovernamental Organistation
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISIMIP	Inter-Sectorial Impact Model Intercomparison Project
JTF	Just Transition Fund
JRC	Joint Research Center
LCA	Life cycle assessment
ML	Machine Learning
NCME	NatCatModelling Engine
NGO	Non-Governamental Organisation
M&A	Mitigation and Adaptation
MAES	Mapping and Assessment of Ecosystems and their Services
P-IAM	Process – Integrated Assessment Model
PAGE	Policy Analysis of the Greenhouse Effect
Plan4EU	European Optimal Electricity System Management Tool
POLES2	Prospective Outlook for the Long-term Energy System model

R&I	Research and Innovation
RCM	Regional Climate Models
SCC	Social Cost of Carbon
SDG	Sustainable Development Goal
SDSS	Spatial Decision Support System
SE	Socioeconomic
SoA	State of the art
STL	Storyline
UNCCD	United Nations Convention to Combat Desertification
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNHCR	United Nations High Commissioner for Refugees
UNFCCC	United Nations Framework Convention on Climate Change
WAREG	European Water Regulators
WHO	World Health Organisation
WMO	World Meteorological Organisation

1. Introduction

This framework provides a structured approach to the co-design and implementation of the CROSSEU methodology for assessing the climate-related socioeconomic risks and develop effective mitigation and adaptation policies at the European scale. By scientific assessment of the existing knowledge, achievements and limitations, including an initial stakeholder engagement phase, and policy gap analysis, this framework aims to provide the support for enhancing the cross-sectoral resilience and sustainability of European societies in the face of climate change, which is the ultimate goal of the project CROSSEU.

This deliverable informs the State of the Art (SoA) review (section 2) linked to the methodological framework for a harmonised socioeconomic risk and impact analysis (section 3). Focussing on the sectoral and cross-sectoral perspective, the SoA includes the recent adances and trends, challenges, limitations and gaps in the research, and describe different biogeophysical (BGP), socioeconomic (SE) and adaptation modelling approaches, as well as stakeholder engagement strategies and existing platforms that faciliate the decision support. The methodological framework details the protocols for the modelling, upscaling and co-designing the Decision Support System (DSS) in the CROSSEU project. Besides, this deliverable presents the results of the first stakeholder engagement process aiming to involve relevant stakeholders in the decision-making process and to gather their input and feedback at the beginning of the project. The initial engagement will secure the effective stakeholder engagement during the project implementation for supporting the identification of potential risks and opportunities, enhance the credibility and reputation of the organisation, and ultimately lead to more sustainable and successful outcomes.

This deliverable outlines the general framework in relation to the SoA, while more in-depth insights are provided in deliverables related to other CROSSEU tasks.

2. State-of-the-art

2.1. Objectives

The SoA synthesises the key information related to the climate change impacts and associated SE risks in Europe, using relevant sources of information (i.e., specialist published literature, research projects, and policy documents). The report underlines the current achievements, barriers and gaps in the research, modelling (BGP, SE and adaptation), and climate policies, considering both the sectorial and cross-sectorial perspectives. This report provides prerequisite information for scoping the co-design process and the overall methodological framework of the CROSSEU project. The results are also used as a reference to be explored throughout the stakeholder engagement process, for provisioning robust actionable science-based information to different users through the CROSSEU DSS.

A systematic review of three main sources of information including academic literature, research projects and policy documents was performed. In addition, the SoA review includes key outputs of initiatives relying on stakeholder engagement that could be relevant for co-designing methodologies, co-production of actionable knowledge and modelling protocols supporting the increase in resilience to SE risks of climate change (Fig. 1).

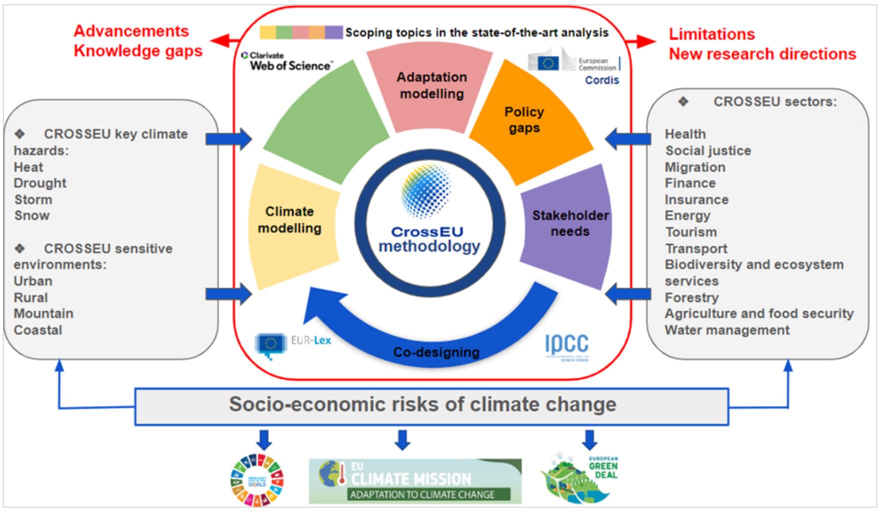

Figure 1. The scoping analysis for co-design and development of the CROSSEU methodological framework

The SoA approach considers the relevant scientific results (i.e., articles, review articles, review chapters), focusing on the socio-economic impacts of climate change and the climate-sensitive sectors across Europe addressed by the CROSSEU project (i.e., health, social justice, migration, finance, insurance, energy, tourism, transport, biodiversity and ecosystem services, forestry, agriculture and food security, and water management). This report also distils and synthesises all relevant information from the official reports of some key intergovernmental organisations such as International Panel of Climate Change (IPCC) (Noble et al., 2014), United Nations Development Programme (UNDP), World Bank, World Health Organisation (WHO), World Meteorological Organisation (WMO), Joint Research Center (JRC), and the European Environment Agency (EEA)[1].

Other sources of information include the key scientific results and outcomes of EU research and innovation (R&I) projects. For this purpose, the European Commission's research database CORDIS (https://cordis.europa.eu/) was interrogated to find relevant EU-funded R&I projects addressing the the climate change impacts and SE risks from different perspectives (i.e., sectorial, cross-sectorial). The SoA integrates the key findings reported by the PESETA projects (JRC), EU FP7 project IMPACT2C, and Horizon 2020 and Horizon Europe projects: COACCH, ENBEL, EXHAUSTION, FARCLIMATE, LOCOMOTION, NAVIGATE, RECONECT, SOCLIMPACT, SPARCCLE.

The SoA also reviews the existing sectorial policy documents relevant for addressing the SE risks of climate change at the European level. In this respect, the investigation is based on the main strategic documents (i.e., strategies and plans) for all CROSSEU sectors which were identified on the EC's Strategy and Policy Platform and the EU law portal EUR-Lex.

2.2. Advances and current research trends

HEALTH. The research achievements in the health sector provide relevant evidence and ensure the scientific baseline for developing or implementing effective and timely climate adaptation (increasing the overall resilience) and mitigation (reducing the greenhouse emissions) measures to minimise climate change impacts at different levels (from national and sub-national to local). The integration of agent-based modelling and tailored causal loops in a complex adaptive system-based

[1] https://www.eea.europa.eu/en/newsroom/news/cities-are-key-to-a-climate-resilient-europe

framework was found to enhance the predictive capabilities in the modelling of health impacts of climate change (Talukder et al., 2024). This framework has been successfully implemented into six health-related systems (i.e., ecological services, extreme weather, infectious diseases, food security, disaster risk management, and clinical public health) and provided valuable inputs for the assessment of health impacts associated with climate change.

Climate change impacts and related risks in the health sector are recognised as significant and some research trends in this sector suggest the need for action using a unified framework. An example in this matter is the One Health and EcoHealth approach that provides the scientific baseline for developing and implementing effective and timely climate adaptation to increase the overall resilience of society. On one hand, One Health [2] is an integrated, unifying approach that aims to sustainably balance and optimise the health of humans, animals, plants and ecosystems (Pitt and Gunn, 2024). On the other hand, EcoHealth is an emerging field that examines the complex relationships among three domains (humans, animals, and the environment), facilitating an improved understanding on how these relationships could affect the health of each of three domains (Lisitza and Wolbring, 2018). In addition, climate mitigation measures are needed to minimise these sectorial impacts at different levels (from global and European to national and local communities) in response to climate change.

Several international organisations operate programmes focused on climate change and health, including CROSSEU partner WMO. The WHO-WMO Joint Office for Climate & Health, together with the US National Oceanic and Atmospheric Administration, spearheads the Global Heat Health Information Network[3]: an independent, voluntary, and member-driven forum of scientists, practitioners, and policy makers focused on improving capacity to protect populations from the avoidable health risks of extreme heat in a changing climate. The European Climate and Health Observatory a partnership between the European Commission, the European Environment Agency (EEA) and several other organisations

[2] https://www.cdc.gov/onehealth/about/index.html#:~:text=One%20Health%20is%20a%20collaborative,plants%2C%20and%20their%20shared%20environment.

[3] https://ghhin.org/about-us/

should be alsso mentioned. The Observatory[4] aims to support Europe in preparing for and adapting to the impacts of climate change on human health by providing access to relevant information and tools. Other important advances in this sector within Europe emerge from the increasingly frequent and prolonged exposure to extreme and health-detrimental heat events of the major cities that are responding with public and policy roles dedicated to delivering and championing solutions to mitigate impacts and health related effects of climate change. Athens, for example, was the first European city to appoint a 'Chief Heat Officer' in 2021[5].

Other advacements are reported by Vicedo-Carbera et al. (2021) , showing that across countries in Europe approximately 20-40% of warm-season heat-related deaths from 1991 to 2018 can be attributed to the anthropogenic climate change, requiring more ambitious adaptation and mitigation strategies to reduce public health risks. Thus, the attribution of climate-related impacts and risks on public health under different climate and socio-economic scenarios could be applied on multiple temporal and spatial scales (from the local ones in urban areas towards global level), based on robust downscaling and upscaling approaches. This is an overall goal from the standpoint of climate change adaptation and mitigation efforts for the health sector. In this context, the IPCC Report (2023) states with very high confidence that actions to limit climate risks for human health will benefit from solutions which integrate mitigation and adaptation measures mainstreaming health into the food, infrastructure, social protection, and water policies. Further research is needed to characterise alternative scenarios, tipping points, effective adaptation and mitigation strategies, as is improved surveillance and linkage between environmental, socio-economic and health data (EASAC, 2019).

SOCIAL JUSTICE. The IPCC's Fifth Assessment Report (2014) highlights that the economic impacts of climate change are likely to exacerbate existing inequalities. The report notes that climate-related economic shocks tend to have more severe consequences for lower-income groups due to their limited adaptive capacity and reliance on climate-sensitive resources. This

[4] https://climateadapt.eea.europa.eu/en/observatory/About/abouttheobservatory/#:~:text=The%20European%20Climate%20and%20Health%20Observatory%20is%20a,by%20providing%20access%20to%20relevant%20information%20and%20tools

[5] https://eurocities.eu/latest/athens-heat-warrior/

is particularly relevant in the context of Europe, where vulnerable populations include small-scale farmers, the elderly, and those in precarious employment situations. Research conducted by Botzen et al. (2019) further supports these findings, showing that the economic costs of extreme weather events, such as floods and storms, disproportionately affect lower-income households in Europe. These households face higher relative damages and have fewer resources to recover, leading to long-term income disparities.

More specifically, Penning-Rowsell and Priest (2015) highlight that the economic losses from flooding in the UK are more burdensome for poorer households, which often lack adequate insurance cover and resources to recover. Paglialunga et al. (2022) show that temperature increases, and precipitation anomalies have a notable negative impact on within-country inequality. This effect is particularly pronounced in regions with a higher percentage of the population residing in rural areas and those working in agriculture.

The most recent IPCC report (2023) shows with high confidence that economic damages from climate change, that have been detected in climate-exposed sectors together with destruction of homes and infrastructure, and loss of property and income, human health and food security, have negative effects on social equity (including gender). This report also reveals with high confidence that in the urban environment observed adverse impacts are also concentrated amongst economically and socially marginalised urban residents. Furthermore, it reveals with very high confidence that projected adverse impacts, risks, and related losses and damages from climate change will grow with every increment of global warming amplifying the challenges related to social justice. The ambitious mitigation pathways (high confidence) have been found to imply large and sometimes disruptive changes in economic structure, with significant distributional consequences, within and between countries, including shifting of income and employment during the transition from high- to low-emissions activities. There is a high confidence in stating that vulnerability to climate change is exacerbated by inequity and marginalisation linked to gender, ethnicity, low incomes, informal settlements, disability, age, and historical and ongoing patterns of inequity such as colonialism, especially for many indigenous peoples and local communities (IPCC, 2023). Vulnerable social groups and communities tend to be more exposed to the diversified and often cumulative risks of being damaged by climate change and the norms targeting it. Yet also, they can be – and they often actually are – among the key actors for managing the climate transition and enact change, particularly when they form groups and networks to collectively address the issues they face (Schor and Thompson, 2014).

The IPCC report (2023) brings into attention, with high confidence, that disaster risk management, early warning systems, climate services and risk spreading and sharing approaches (e.g., weather and health insurance, social protection and adaptive social safety nets) can be applied across sectors. These measures have the potential (which must be further assessed in detail) to reduce social disparities and enforce social justice. Increasing education including capacity building, climate literacy, and information provided through climate services and community approaches can facilitate heightened risk perception and accelerate behavioural changes and planning with benefits for social justice. There is also a high confidence associated to prioritising equity, climate justice, social justice, inclusion and just transition processes can enable adaptation and ambitious mitigation actions and climate resilient development.

Looking at the European Union, in 2021, the EC established the Just Transition Fund (JTF)[6], to provide support to Member States that identify regions expected to be highly negatively impacted by the transition towards climate-neutrality. The goal of the JTF is to support and help deliver economic diversification and recovery in regions that might otherwise suffer and be left behind in a net-zero economic Europe. Just transition actions are particularly important in addressing gender inequality resulting from climate change because women are more likely to experience job losses in climate-sensitive sectors and have fewer opportunities to transition into new employment areas (Jordan et al., 2021). Beyond JTF, the EC is developing projects aiming to understand the impact of the European Green Deal (EGD) policies on vulnerable groups, prevent inequalities that could be generated by these policies, and produce knowledge and innovations to advance behavioural change at individual and collective levels for an inclusive and equal EGD. In regard to this, the new Social Climate Fund dedicates €65 billion from the EU budget, and over €86 billion in total to support the most vulnerable citizens and small businesses with the green transition. This is to ensure there are

[6] https://ec.europa.eu/regional_policy/funding/just-transition-fund/just-transition-platform/about_en

opportunities for everyone, by tackling inequality and energy poverty, and strengthening the competitiveness of European companies, leaving no one behind.

In addition, many Non-Governmental Organisations (NGOs) and Inter-Governmental Organisations (IGOs) (such as the International Federation of Red Cross and Red Crescent Societies - IFRC, Save the Children, or Oxfam) focus much of their attention on a just transition in response to climate change impacts. Another hitherto neglected aspect of social justice and climate change is the impact of eco-anxiety, especially in young people living in countries and regions subject to extreme weather events made more frequent, intense, widespread, and prolonged by climate change.

"Social justice" is virtually linked to all the other sectors considered in the CROSSEU project. Looking at the health sector, for example, Kovats & Hajat (2008) discuss the economic losses from climate-related health issues, such as heat stress and vector-borne diseases, which are more pronounced among low-income populations due to limited access to healthcare and greater exposure to environmental hazards.

Looking more in depth at gender inequality at European level, this phenomenon is significantly impacted by climate change. Women, particularly those in rural and lower-income communities, are more vulnerable to the adverse effects of climate change due to existing social and economic disparities. According to Jordan et al. (2020), women are more likely to experience job losses in climate-sensitive sectors and have fewer opportunities to transition into new employment areas, thereby increasing economic disparities between men and women. According to Dankelman (2010), women are more likely to be engaged in sectors such as agriculture and tourism, which are highly sensitive to climate change.

The gender impacts of climate change are also evident in the labour market. For instance, MacGregor et al. (2012), argue that climate change can increase the burden of unpaid care work on women, particularly in low-income households. This increased burden limits women's economic opportunities and exacerbates existing gender disparities in income and employment. The intersectionality of income, wealth, and gender inequalities reveals a complex web of socioeconomic disparities exacerbated by climate change. These inequalities are not isolated but interact in ways that compound their effects. For instance, low-income women in Southern Europe face a double burden of income and gender inequality, making them particularly vulnerable to climate impacts (Lomborg, 2020).

MIGRATION. Migration is a process that may build capacity and sustainability for a climate-disrupted future (McLeman, 2019). The most recent IPCC Report (2023) indicates that climate change will drive population movements by making certain parts of the world much less viable places to live; by causing food and water supplies to become more unreliable and increasing the frequency and severity of floods and storms. To better conceptualise the phenomenon of climate migration, the literature has developed clearer definitions and typologies of climate migration, distinguishing between voluntary and forced migration and identifying different causes, such as sudden onset disasters (e.g. hurricanes, floods) and slow onset changes (e.g. desertification, sea level rise). IPCC (2023) also states with high confidence that prioritising equity, climate justice, social justice, inclusion and just transition processes can enable adaptation and ambitious mitigation actions and climate resilient development. In this respect it is important for future research to go beyond fear from climate migration (Nash and Zickgraf, 2020) but respond by setting priorities into combating climate change and not the climate related migration itself. While the current policy framework already allows accommodating environmentally induced displacement to some extent, better integration is needed.

FINANCE. Climate change impacts the global financial system targeting the physical risks (such as those determined by the extreme weather events) and transition risks (stemming from policy changes and economic transitions towards low carbon technologies). Steps towards the integration of climate science with the financial risk analysis have been made but are still needed. Calvet et al. (2022) shows a strong connection between climate sciences and finance, as financial markets may be influenced by various climate-related risks. There are four subcategories of the analytical efforts towards the integration of climate change issues in the finance sector: financial losses (analysing the effects of climate on financial asset returns, including stranded assets) that could have a direct or indirect impact on the markets; environmental uncertainty (examining the influence of climate variables on economic variables); economic climate risk (analysing the impact of climate on the economy and markets); and climate policy risk (assessing the risk of new regulations on business and economic performance). Production and consumption interruptions, a decline in asset value, economic harm, trade barriers, and political instability are all potential consequences of climate change that could put assets and financial portfolios at risk.

Between 2021 and 2022, a global average of 1.3 trillion USD in climate finance was committed by public, corporate, international, and domestic financial entities, according to the 2023 Global Landscape of Climate Finance. This represents a nearly twofold increase above the USD 653 billion tracked on average over 2019–2020. A small group of countries, China, the United States, Japan, and India, have accelerated their investments in clean energy, accounting for 90% of the additional funding, which has led to this growth. Over the past two years, adaptation funding has increased more modestly while mitigation finance has surged substantially. Just USD 63 billion, or 5% of the total, was set aside especially for financing adaptation (compared to 7% in 2019–2020). In developing countries the funding gap for adaptation is widening, being four times higher than in developed countries (The Global Center on Adaptation, 2023).

INSURANCE. Climate risk insurance research has developed in the last decades by proposing different methods and tools such as insurance schemes against extreme weather conditions, weather index insurance, cost-benefit analysis, and early warning systems (Lin Y.-H et al., 2023). However, many issues remain open research questions. For example, how can differences between natural climate variability and anthropogenic driven climate change be distinguished, accurately attributed, or quantified – and how will these differences impact on insurance products or climate adaptation and mitigation strategies? How can the outputs of climate models be best leveraged to analyse future physical and transitional climate impacts? How can uncertainty be accurately quantified in climate model projections? What is the impact on insurance products if AI (machine learning) based weather and climate forecasting tools continue to emerge and, in some ways, improve on existing physics based numerical weather prediction?

ENERGY. Climate change poses significant risks to various sectors globally, with the energy sector being particularly vulnerable. The impact of climate change on energy systems is multifaceted, affecting everything from energy production and infrastructure to demand and policy (IPCC, 2023). In a recent WMO review regarding the renewable energy potential resources and the energy demand highlight climate variability significantly affects renewable energy indicators, with notable anomalies in wind and solar power outputs across countries (WMO, 2023). Additionally, incorporating climate variability into energy strategies and improving data collection can enhance renewable energy deployment, especially in developing regions. The state of knowledge of climate change impacts on energy systems shows a predilect focus on the cooling or heating demand of buildings, either at the regional or global scale (Li et al., 2012). One of the primary achievements in this field is the development and refinement of methodologies to assess climate change impacts on energy systems. Researchers have employed a wide array of models and datasets to understand the complex interactions between climate variables and energy infrastructure (Emodi et al., 2019, Tobin et al., 2018, Craig et al., 2018). These models range from climate simulation models, which project future climate scenarios, to energy system models, which predict how these scenarios will affect energy supply and demand. In this regard, the use of integrated assessment models (IAMs) has been particularly noteworthy (Aaheim et al., 2009). IAMs combine knowledge from various disciplines to assess climate change impacts holistically, considering economic, environmental, and social dimensions and provide information on how climate change might influence energy prices, resource availability, and infrastructure resilience (Weyant, 2017). Recent literature has provided a wealth information of climate change impacts on energy production and supply (Emodi et al., 2019, Cronin et al., 2018), on the one side, and on energy demand (Chandramowli & Felder, 2014, Auffhammer and Mansur, 2014, Schaefer et al., 2012), on the other side. Energy infrastructure (e.g., power lines, oil and gas pipelines, and production facilities is increasingly vulnerable to extreme weather events. The literature documents numerous examples where floods, wildfires, and hurricanes have disrupted energy supply chains (Schaeffer et al., 2012). The growing understanding of climate change impacts has led to the development of various mitigation and adaptation strategies within the energy sector (Grafakos, 2020). In this matter, a major focus has been given on reducing greenhouse gas emissions through the transition to renewable energy sources such as wind, solar, and hydropower (Hassan, 2024, IRENA, 2020). The efforts in climate adaptation strategies have been made by reinforcing physical structures, improving grid management and developing smart grids that can handle variability in supply and demand (Hernandez et al., 2020, Lund et al., 2015). In this light, the achievements in understanding and addressing the impacts of climate change on the energy sector are significant. Through advanced modelling of comprehensive risk assessments, and the development of robust mitigation and adaptation strategies, the energy sector is better equipped to handle the challenges posed by a changing climate.

The EU Copernicus Climate Change Service (C3S) has developed an operational climate service C3S Energy, that has been designed to enable the energy industry and policymakers in Europe. The C3S Energy Service covers different time horizons (the past 40 years and future). It provides a time series of electricity demand and supply from wind, solar photovoltaic and hydropower, and can be used for recent trends analysis, seasonal outlooks or the assessment of climate change impacts on energy mixes in the long term (Dubus et al., 2023). This service will be updated with the integration of the new climate projections available within the Coupled Model Intercomparison Project 6th phase (Eyring et al., 2016).

One of the prominent research priorities identified is the deeper focus on the climate change impacts on the energy systems in the developing countries. However, the goal of assessing climate change impacts on the energy sector can be limited by the diversity of methodologies and datasets employed in current literature, resulting in considerable variability in study outcomes. Therefore, implementing a consistent multi-model assessment framework to support energy planning at regional to global scales is needed (Yalew, 2020).

At European level, the renewables and wind energy sectors managed by large industry bodies such as Wind Europe, work actively with a broad suite of external stakeholders (including academia) to identify research gaps and priorities in the context of the emergent climate change challenges. For example, the March 2024, the annual WindEurope[7] conference included a hackathon, which discussed and targeted relevant climate-issues for the energy sector such as: the changing climate patterns and conditions; offshore wind power; fuel efficient routing; cross-border pollution; Generative AI: ocean data discovery and interaction; and spatial asset distribution.

TOURISM. To date, there have been several noteworthy achievements in the field of tourism and climate change research. The growing concern of climate change impacts in different sectors in policy, particularly after the Paris climate agreement, has stimulated climate change research with a focus on the tourism sector over the recent decades. Furthermore, the development of the Tourism Climate Change Knowledge System (Loehr &

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[7] https://windeurope.org/annual2024/hackathon/#use-cases

Becken, 2021) has provided a comprehensive framework for the evaluation and integration of knowledge in academia, practice and policy. This system emphasises the importance of systems thinking and the necessity for holistic approaches to managing climate risks. Concurrently, the growing recognition of the tourism sector's role in contributing to and being affected by climate change has also led to an increasing amount of research focusing on reducing greenhouse gas emissions and promoting sustainable practices within the sector (Peeters et al., 2024, Steiger et al., 2022, Loehr and Becken, 2021).

The effective use of quantitative research techniques, such as trend analysis and time series analysis, has yielded valuable insights into climate change's impacts on tourism. Geographic Information Systems (GIS) have been instrumental in the study of these effects, offering a powerful tool for data visualisation and analysis. In addition, climate change models have been adopted to project future scenarios for tourism destinations, assisting policy makers and stakeholders in planning and preparing for the impacts of climate change. A notable result of the intersection of climate change and tourism research is the increase in awareness and attention to the sustainability of tourism practices and reducing carbon emissions within the tourism sector. As a follow up, destination managers are currently actively seeking solutions to decarbonise tourism operations. Furthermore, a shift in focus from merely understanding the impacts on businesses to considering the broader destination level, which includes a variety of stakeholders, local communities and environmental resources has taken place This shift is crucial for the development of comprehensive strategies that improve resilience and sustainability in tourism. Indeed, the EU has recognised the potential of ecotourism and agro-tourism, which contribute to biodiversity conservation, income diversification, job creation and the prevention of depopulation. Support for these forms of tourism has led to better living conditions and the preservation of natural and cultural heritage. Agro-tourism emerges as a source of additional income for farming families and can promote local products and traditional crafts, adding value to agricultural production (Dube 2024, Pan et al., 2023, Sajn &Finer, 2023, Köberl et al., 2016).

One of the key tourism industries impacted by a warming climate in Europe is the winter sports sector, as snow coverage retreats to higher altitudes for shorter seasons, making the economics of many Alpine resorts very difficult in the future, especially at altitudes lower than 2,000 m (Mitterwallner et al., 2024). How resorts respond – for example, by pivoting to focus on attracting visitors year-round – is also impacted by a nexus of issues including: energy use, environmental impacts, and water conservation. These are all part of the problem, since higher temperatures do not merely reduce the quantity and quality of natural snow available to resorts – they also reduce resorts' ability to generate and retain artificial snow. Snowmaking requires substantial energy and water use, which has financial, carbon footprint, and environmental ramifications for resorts. (François et al., 2023).

Future research relevant for the tourism sector should address the previously identified gaps and limitations, including the need to include a broader range of voices and improve collaboration between different geographical regions. This should include prioritising research on vulnerable and underrepresented regions to ensure that their unique challenges and needs are addressed. Furthermore, more holistic studies that integrate various aspects of tourism, including transport modes and domestic tourism, are needed to provide a clearer picture of the sector's climate resilience. This includes the creation of adaptive measures for tourism infrastructure, the promotion of sustainable tourism practices and the integration of climate resilience into tourism planning and policy frameworks. The development of more robust theoretical frameworks and the improvement of data collection methods will also be crucial. Future research should prioritise the development of integrated, multidisciplinary approaches that bridge the gap between scientific knowledge and practical application. Furthermore, the exploration of innovative solutions to improve the resilience of tourism destinations while ensuring the socioeconomic well-being of tourism-dependent communities is essential. Building stronger collaborations between academia, industry and policy makers will be essential to advance knowledge and the implementation of effective climate change strategies in tourism. Integrating different methodological approaches and promoting interdisciplinary collaboration will be crucial for advancing understanding of climate change and tourism. Transport, mobility and domestic tourism should be fully integrated in tourism research in relation to climate change mitigation (Peeters et al., 2024). Including a disaster risk perspective in tourism research and documenting loss and damage in relation to climate change would contribute to better defining adaptation and resilience building measures (Dube, 2024). By addressing these priorities, the tourism sector can better prepare and adapt to current and future impacts of climate change, ensuring its sustainability and resilience (Dube, 2024, Peeters et al., 2024, Loehr and Becken, 2021).

TRANSPORT. European projects like INFRARISK, addressing risk assessment (Clarke & O'Brien, 2016), RAIN and RESIN on critical infrastructure vulnerability (O'Brien et al., 2015), INTACT - resilience of infrastructure (Reder et al., 2018), WEATHER, with an analysis of economic losses (Doll et al., 2012) have improved the general understanding the impacts of extreme weatherevents on transport infrastructure and stimulated the development of decision-making tools (Sotirios, 2019). However, a systematic assessment of specific infrastructure vulnerability of the transport sector is still needed.

BIODIVERSITY AND ECOSYSTEM SERVICES. Ecosystem services are the benefits that humans derive from ecosystems, including provisioning, regulating, cultural, and supporting services. Climate change threatens ecosystems as life supporting units and also all these services in multiple ways. Climate change is also one of the main drivers of biodiversity loss and ecosystem degradation, with a widely recognised critical role along with other non-climate pressures such as alien species invasions, habitat fragmentation, air pollution, anthropic exploitation of resources and land degradation (EEA, 2024, IPBES 2019, IPCC 2013, Pereira et al., 2012). Considering the expected threats that climate change is posing to future biodiversity, with expected adverse impacts across various European regions and ecosystems, consistent efforts have been made to understand and assess the impacts on terrestrial, freshwater, coastal, and marine ecosystems simultaneously, and of cross-ecosystem impacts (Gounand et al., 2018, Loreau et al., 2003). Large-scale assessments of biodiversity change in response to climate change have tended to look only at direct impacts of climate change on biophysical conditions using either a traits-based approach (Foden et al., 2013) or species distribution modelling (Warren et al., 2018) or alternatively consider habitat loss and fragmentation alone.

Climate change hotspots for biodiversity pinpoint areas where climate change is very likey to have significant impacts on biodiversity, that are of particular concern for conservation efforts, but also insufficiently tackled by quantitative analysis (Cheval et al., 2020, Turco et al., 2015). The research progress would support enhancing the climate resilience of ecosystems, protecting critical habitats, and enabling species to adapt to changing conditions.

The advancement in the Earth Observation technologies determined an extensive use of remote sensing in mapping the supply and demand of ecosystem services. Recent research focusing on biodiversity and ecosystem service issues relies on the use of a wide range of satellite-derived products (images and indeces) together with environmental variables that support the provision of quantitative and spatially explicit estimates of different biophysical parameters as proxies for several ecosystem services (e.g., NDVI, NDWI, land temperature, NPP models, vegetation phenology).

Understanding how biodiversity and the provision of ecosystem services respond to the combined action of natural and anthropic drivers and to the pressure of climate change requires a multi-faceted approach. Price et al. (2024) develops a spatially explicit methodology to assess this globally and nationally using large scale datasets. An even more detailed approach would be appropriate at the case study scale and would involve:

- ✓ use of long-term environmental data and related long-term integrated monitoring for the identification, investigation and prediction of trends and developments in ecosystems;
- ✓ use of transdisciplinarity in the selection of ecosystem services and their indicators - stakeholders' involvement in identifying ecosystem services based on local knowledge and perception and use of citizen science for biodiversity observation and quantifications of ecosystem services supply and demand;
- ✓ data fusion linking Earth Observation with in-situ data from automated stations, statistical data and expert knowledge;
- ✓ data visualisation through accessible web platforms.

FORESTRY. Forestry research benefits from recent enormous advances in the development of remote-sensing techniques and the continuous growth in computing capabilities, fostering enhanced understanding of population features, but also of the structure and spatial distribution of trees (and individual trees) over vast areas and at different levels (Coops et al., 2021). O'Sullivan et al. (2021) also underlined the added value of such tools (i.e., terrestrial laser scanning) in investigation of ecological and evolutionary processes of forest communities and the interactions between them. Overall, biogeophysical modelling has contributed to improved understanding of changes in the forest cover, structure, composition and shifts in the biophysical processes (i.e., the water and energy balances), which further may enhance or diminish the climate change effects on biomass and carbon stocks from forests and its related activities. Forest landscape modelling has also been subject to significant improvements over time, with enhanced model spatial and temporal resolutions and a better integration of ecological processes (Scheller, 2018).

In addition, socio-economic modelling is also a critical tool for understanding the impacts and risks of climate change in the forestry sector. Economic mechanism models quantitatively assess the impact of climate change on different economic systems from an economic perspective. These models include the Ricardian model (Chen et al., 2013), computable general equilibrium (CGE) model (Kunimitsu, 2015), and economy-climate (C-D-C) model (Chou et al., 2011, Chou & Ye, 2006). The latter model allows the integration of climatic and economic factors and could consider the long-term climate trends, providing valuable insights for understanding the impacts and risks of climate change (Chou et al., 2021).

Highly overlooked but lately taken into consideration, citizen science and the multi-actor approach has been slowly but steadily complementing modelling and research approaches in forestry. Many projects are actively engaging actors and relevant associations to either validate the results or build community knowledge on various domains associated with forestry (Fauzi et al., 2024). Even though it is mostly applied in post-border scenarios (after an event has happened), its efficiency has increased the capacity for biosecurity and management practices throughout the entire value-based chain (Hulbert et al., 2023).

Overall, an improved understanding of future climate change impacts on forests and the development of effective adaptation strategies relies on the following research priorities:

(i) improved climate-forest modelling frameworks, with improved abilities to simulate the effects of extreme weather events on forests (Blanco & Lo, 2023, Hlásny et al., 2022). Furthermore, new developments for automatic and climate-sensitive tree monitoring (Sethi et al., 2022) and correlational (management-friendly) approaches (i.e., allometric and inventory-based models) are needed (Ordoñez et al., 2020); all these new efforts are expected to enhance the of accuracy of projections and scenarios at regional and local scale;

(ii) in-depth investigation of responses of forest types and species (i.e., composition, habitat connectivity, ecosystem services) to different climate stressors, changing environmental conditions and associated disturbances

(Machado Nunes Romeiro et al., 2022) ; this is a research priority to identify the most resilient forest species and ecosystems for improved forest management practices, conservation actions and adaptation options;

(iii) analysis on the potential of forests and ecosystems to sequestrate and store carbon under the changing climate (Nunes et al., 2019); this research direction will support the forest carbon management strategies;

(iv) integrated assessment approaches allowing the assimilation of remote data sensing data or relying on remote sensing techniques (i.e., LiDAR measurements) that could contribute to an improved accuracy of model output sat local scales (i.e., estimations of energy and C fluxes) (Bannister et al., 2022, Olpenda et al., 2018);

(v) involvement of stakeholders who are not modellers into the forest modelling process – the forest modelling is increasingly acknowledged as a community and interdisciplinary effort (Blanco and Lo, 2023). The increasing need for tailored climate-forest information has increased the importance of stakeholder engagement (and co-design) activities to bridge the gap between science, practice and decision-making and to keep up with the knowledge demands in the forestry sector for effective management and adaptation;

(vi) development of collaborative solutions and tools (i.e., co-designed policy and decision-making support systems) with end users (i.e., stakeholders); such instruments could support policies, improve compliance with regulation and policy, consider regional and local differences and lead to long-term sustainable behaviours in forest management (McIntyre & Schultz, 2020).

AGRICULTURE AND FOOD SECURITY. The agriculture sector globally is subject to a concerning scenario, as sufficient production and food supplies are threatened due to irreversible weather fluctuations, under both present and future climate change (Abbass et al., 2022). In such a context, biogeophysical (BGP) modelling provides key inputs for impact assessments for the agriculture sector, in relation to the increasing frequency of climate extreme events.

Climate change generates a wide range of impacts at both sectorial and cross–sectorial levels. Agriculture is one of the key sensitive sectors to climate change, showing recurrently affected agricultural yields in numerous regions of Europe and worldwide (Hristov et al., 2023, Olesen et al., 2011). The food system is subject to consistent transformations under climate change which plays a critical role in the depletion of natural resources (i.e., land, water) and increasing risks to agricultural productions due to extreme weather events.

Remote sensing technology is crucial in modern agriculture for crop monitoring and evaluation, significantly transforming agriculture — a cornerstone of global food security (Karmakar et al., 2024). This technology enables several critical functions, including the use of vegetation indices, satellite imaging, and early pest and disease detection. These capabilities collectively enhance crop yield estimation and production scheduling, thereby supporting various aspects of agricultural planning and management.

Earth-observing satellites like NASA's MODIS and ESA's Sentinel series offer extensive data across visible, near-infrared, and thermal infrared wavelengths. For example, Sentinel-2's high-resolution multispectral data enables precise monitoring of crop health and land use patterns. Specialists use these data to identify crop types by analysing their unique spectral fingerprints, creating detailed crop-type maps. This information aids in land use planning, resource allocation, and optimising agricultural practices.

Additionally, satellites facilitate the continuous observation of crop growth throughout the growing season. Instruments like MODIS provide global coverage to monitor vegetation "greenness" using vegetation indices such as the Normalised Difference Vegetation Index (NDVI), which measures plant photosynthetic activity. NDVI trends help assess crop health and predict yields, with rising NDVI indicating healthy crops and falling NDVI signalling stress from factors like nutrient deficiencies, diseases, or drought. By analysing these trends, farmers can make informed decisions on irrigation, fertiliser, and pest management to enhance crop yields (Sahoo et al., 2024). Other key vegetation indices are: Enhanced Vegetation Index (EVI), an improved version of NDVI that has increased sensitivity to vegetation cover while decreasing sensitivity to atmospheric conditions, usually used to monitor dense vegetation; Normalised Difference Water Index (NDWI) primarily used to detect water content in vegetation and soil (identifying water stress, which is a critical factor impacting crop health); SAVI (Soil-Adjusted Vegetation Index) intended to reduce the impact of soil brightness on vegetation indices; Leaf Area Index (LAI) used to assess the density of the vegetation cover and offer information about crop growth and productivity (a key variable in many models describing vegetation-atmosphere interactions, particularly with respect to the carbon and water cycles).

As the global population grows, the demand for food is increasing rapidly, necessitating that the agricultural industry produce more food using fewer resources and with minimal environmental impact. Crop production forecasting is crucial in modern agriculture for planning, optimising yields, and ensuring food security. Remote sensing emerges as a promising technology for this purpose, offering accurate and timely data on crop health, growth, and yield. Furthermore, remote sensing has found successful applications in various crop production forecasting initiatives globally. One notable instance is the European company HEMAV, which leverages satellite data to estimate crop yields across Europe (https://hemav.com/en/). HEMAV's system offers precise and timely insights into crop growth and yield, empowering farmers to enhance their crop management strategies and aiding agribusinesses in formulating marketing plans. Another notable application is the Agricultural Stress Index System (ASIS) (Rojas, 2021), developed by the Food and Agriculture Organisation (FAO) of the United Nations. ASIS utilises satellite data to monitor crop stress indicators such as drought, pests, and diseases, issuing early warning alerts to farmers and governments. ASIS has proven effective in multiple Latin American countries, assisting farmers in improving crop management efficiency and addressing climate change impacts.

Current remote sensing models for crop yield estimation face challenges such as insufficient generalisation ability, monitoring timeliness, and detailed mapping of yields, hindering their applicability in precision agriculture. However, advancements in high-resolution remote sensing data and deep learning technology offer a promising direction. Coupling deep learning with crop growth models to construct scalable and efficient crop yield estimation models could address these challenges. Utilising crop growth models to simulate growth under various conditions and applying deep learning to model complex situations and achieve spatial extrapolation shows potential for future research. Despite the opportunities presented by AI-driven remote sensing for climate and crop monitoring, several challenges need addressing for effective implementation (Han et al., 2024). While remote sensing technology has seen significant growth in precision agriculture, there is a need to develop accessible yet reliable workflows for real-time applications, considering the complexities of image processing and technical expertise required. Creating accurate and user-friendly systems is crucial for wider adoption of remote sensing technologies in both commercial and non-commercial precision agriculture. Remote sensing offers farmers numerous benefits, including enhanced crop yields, lower input costs, and reduced environmental impact. It allows farmers to monitor crop health and growth, identify stress factors early, optimise irrigation and fertilisation, and plan harvests effectively. Furthermore, remote sensing assists farmers in mitigating risks such as climate change, pests, and diseases by issuing early warning alerts and facilitating timely interventions. Additionally, it enables farmers to access new markets and value chains by providing insights into the quality and origin of their crops. Remote sensing for crop production forecasting is advancing, with new developments emerging. Artificial intelligence (AI) and machine learning (ML) are promising for analysing remote sensing data, extracting more information, and improving forecast accuracy. Hyperspectral sensors offer detailed data on crops' biochemical properties, aiding in precise yield estimates and stress detection. Integrating remote sensing with precision agriculture and blockchain enhances understanding and efficiency in crop production ecosystems. These advancements hold potential for more sustainable and efficient agriculture (Katyauripo et al., 2023).

Overall, the future of remote sensing applications in food security is poised for significant growth and evolution. In the future, several key trends and developments are expected to influence the role of remote sensing in ensuring food security (Karthikeyan et al., 2020):

(i) Increased use of ML and AI: With the advancement of remote sensing technology, machine learning and AI will play a crucial role in analysing and interpreting data. This will enable more accurate and timely predictions of crop yields, weather patterns, and other factors affecting food security.

(ii) Greater integration with other technologies: Remote sensing will increasingly integrate with other technologies like ground observations, computer models, and geospatial data. This integration will lead to more comprehensive and accurate analyses of food security, enhancing our understanding of Earth's systems and processes.

(iii) Growing use of drones and unmanned platforms: Drones and unmanned platforms offer advantages over traditional satellite and aircraft platforms. They can be deployed quickly and operate at lower altitudes, capturing more detailed and accurate data. As these technologies mature, they will play an increasingly important role in food security.

(iv) Expansion in disaster management: Remote sensing is valuable for managing and responding to natural disasters such as droughts, floods, and storms, which significantly impact food security. With the expected increase in frequency and severity of these events due to climate change, remote sensing will see expanded use in disaster management.

WATER MANAGEMENT. Water resources are critically important to a wide range of sectors, socio-economic activities and communities, but they are also valuable due to their high biodiversity and ecosystem services they provide (John et al., 2020). There are promising advancements on the integration of climate resilience into water management, with significant improvements in wastewater treatment (Ciampittiello et al., 2024), desalination, rainwater harvesting, and improved irrigation techniques that can help countries adapt to a changing climate. Water management practices in Europe have the potential for significant achievements in adapting to climate change. For example:

- Implementing advanced weather forecasting systems and real-time water monitoring allows for proactive management of water resources during droughts and floods (Global Water Partnership, 2009);

- Developing more flexible water allocation systems that can adapt to changing water availability ensures all sectors (agriculture, industry, households) have access to water during both wet and dry periods (UNEP, 2018);

- Using Nature-based solutions by utilising natural ecosystems for water management, such as restoring wetlands and floodplains, can improve water storage, filtration, and flood protection (UNEP, 2018);

- Upgrading water infrastructure to reduce leakage from pipes and canals can significantly conserve water resources (UNEP, 2018);

- Implementing water reuse and recycling programs in agriculture and industry can reduce freshwater demand (WateReuse Association, 2018);

- Implementing integrated water resources management to coordinate the management of water and other resources (e.g. soil), to maximise social wellbeing in a sustainable and equitable manner (Ciampittiello et al., 2024);

- Utilising smart irrigation technologies that optimise water use in agriculture can significantly improve water efficiency;

- Educating the public about water conservation and the importance of sustainable water practices can lead to significant reductions in water demand.

By focusing on these, European water management can become more resilient, efficient, and adaptable in the face of climate change.

Available studies suggest human activity will be the primary driver of global water scarcity in the future. However, on a regional level, the high uncertainty surrounding climate change predictions makes reduced water availability a more likely outcome in many major river basins. Even in basins expected to see increased water availability due to climate change, the risk remains significant. These substantial uncertainties in future water scarcity pose significant challenges for water management policies and planning. Therefore, regions with high projected water scarcity and significant uncertainty should be prioritised for robust water management policy development (IPCC, 2022).

Building on the research gaps identified earlier, key research directions and priorities for water adaptation measures include:

- ✓ Conduct long-term studies to assess how current adaptation measures perform under various future climate scenarios. This will help identify robust and adaptable strategies;
- ✓ Research and develop adaptation measures tailored to specific regions, considering factors like climate projections, existing infrastructure capabilities, and social contexts;
- ✓ Develop decision-support systems (DSS) that can help water managers select and implement the most suitable adaptation strategies for their specific region. Such systems have the added benefit of fostering social engagement and learning;
- ✓ Research how water adaptation measures can be effectively integrated with other sectors like agriculture, energy, and urban planning to achieve maximum benefits for water security and overall sustainability;
- ✓ Develop models and simulations to assess the effectiveness of integrated water management approaches under different climate and socio-economic scenarios;
- ✓ Research the social and economic implications of water adaptation measures, particularly on vulnerable communities. This includes investigating equitable water allocation strategies during droughts;

- ✓ Explore how to ensure public acceptance and participation in the development and implementation of water adaptation measures;
- ✓ Research on how to optimise the use of natural ecosystems for water management (e.g., wetland restoration) in different climatic and geographic settings;
- ✓ Evaluate the cost-effectiveness of nature-based solutions compared to traditional grey infrastructure for water management under various climate scenarios;
- ✓ Research on innovative financing mechanisms for implementing and maintaining water adaptation measures;
- ✓ Future research efforts in water management under climate change should also focus on dynamic adaptation strategies that holistically consider socio-political contexts, biodiversity conservation and the maintenance of ecosystem services.

2.3. Challenges, limitations, and gaps

The project addresses the relevant challenges related to the increasing climate pressure on the CROSSEU selected sectors. This section syntheses the key findings hereafter.

HEALTH. The challenges related to the assessment of climate change impacts on the health sector are still particularly complex. Evidence-based research shows that climate change affects the health sector, resulting in increased health burdens due to extreme heat-related morbidity and mortality (van Daalen et al., 2024, IPCC, 2023, Vicedo-Cabrera et al., 2021). In Europe, heat waves are the deadliest atmospheric hazard (Douris & Kim 2021). Studies suggest that under high-emission scenarios, the increase in excess mortality due to hotter summers may surpass the decline in cold-related mortality from milder winters if no adaptation measures are implemented (Martinez-Solanas et al., 2021, Feyen et al., 2020, Vicedo-Cabrera et al., 2018, Gasparrini et al., 2017).

Besides direct effects on human morbidity and mortality, high temperatures and heat waves have adverse effects on mental health and wellbeing (Thompson et al., 2023). Even slight temperature increases can diminish cognitive and physical performance, thus affecting labour productivity and earning capacity (EASAC, 2019, Gosling et al., 2018, Dasgupta et al., 2021). Any changes in productivity have macroeconomic implications, affecting national income (Day et al., 2018). While earlier analyses had concentrated on the effects of heat on rural/outdoor labour capacity (Ioannou et al. 2022), recent studies show that many occupations may be affected. For example, recent analysis by the French Agency for Food, Environmental, Occupational Health and Safety (ANSES, 2018) concludes that productivity and health of workers in most business sectors will be affected in European countries by 2050. Ciscar et al. (2018) suggest that for temperature rises greater than 2°C, labour productivity could drop by 10–15% in some southern European countries.

As drop in labour productivity is expected to be largest in the countries with the largest proportion of workers in heavy physical occupations (Ciscar et al. 2018), climate change has the potential to increase social-economic inequalities. Socio-economic differences such as age, sex, education, and income are all important factors that differentiate population groups most vulnerable to climate-related risks (Masselot et al., 2023). Future changes in vulnerability factors such as growing elderly populations or increased levels of social deprivation will be a key component of future heat-related risks, alongside climate change (Jenkins et al., 2022). Alongside the need to consider inequality when modelling heat-related risk, recent studies (Jánoš et al., 2023, Ellena et al., 2022) also highlight the importance of taking into account socio-economic inequalities in designing strategies for mitigating the impacts of climate change on human health.

Climate change is also expected to indirectly affect the health sector. Rising global temperature will lead to the seasons and geographical distribution of many vector-borne diseases, such as malaria, dengue, Lyme disease, and West Nile fever, potentially expanding to higher altitudes and latitudes (Semenza & Suk, 2018). Additionally, prolonged vegetation seasons and increased CO_2 concentrations may lead to higher pollen production and an increase in allergic diseases (Singh & Kumar, 2022, EASAC, 2019). Moreover, higher frequency of droughts and wildfires may have negative impacts on water and air quality and exacerbate food insecurity which all affect public health (IPCC, 2023). Furthermore, climate-related increases in flood risk may reduce water quality and increase the prevalence of water borne diseases in certain regions (IPCC, 2023). All these impacts are recognised as significant and require action (EASAC, 2019). However, there are several limiting factors in the analysis of the health impacts and risks of climate change (Ebi, 2022, Wardekker et al., 2012) such as: (i) lack of data (including the limited access to fine-scale health outcome data due to confidentiality laws and regulations), (ii) multi-causality, (iii) unknown impacts considering a high-quality health system, (iv) complex cause-effect relations leading to multi-directional impacts, (v) possible changes of present-day response-relations, and (vi) difficulties in predicting local climate impacts. Attribution of health impacts, projection of future climate change risks and the link between climate change and the non-endemic vector-borne diseases are additional challenges for understanding the climate change impacts in the sector from the adaptation perspective and for developing effective responses.

Other important limitations are related to the assumption of no physiological and socio-economic adaptation to the warmer climate (Gosling et al., 2017) nor changes in the demographic structures of populations (Rai et al., 2019). Several studies considered long-term changes in the exposure-response relationship when modelling the impacts of climate change on temperature-related mortality (Jenkins et al., 2022, Huber at al., 2022, Gosling et al., 2017). However, as only a few authors used the empirical evidence of past adaptation to future projections, one needs to be aware that all approaches imply simplistic assumptions on the form of the future exposure–response shape and its changes due to adaptation. This results in uncertainties due to the adaptation scenarios in future projections that are, according to Gosling et al. (2017), larger than those related to climate models and emission scenarios. Additional uncertainties in future projections have been related to differences between epidemiological models used to estimate the exposure-response function (Benhmarnia et al., 2015). Thus, simple extrapolation of current relationships with higher temperatures without considering changes in socioeconomic and demographic aspects may significantly misestimate the real effects (Jenkins et al., 2022).

While the health co-benefits of climate change mitigation are clear (Chang et al., 2017, Whitmee et al., 2015, Haines et al., 2009), understanding the economic costs and benefits of climate change impacts on the health sector remains limited (Berrang-Ford et al., 2021), with gaps highlighted by the WHO (2021), including: (i) financial estimations of health impacts, (ii) the potential health co-benefits and trade-offs of climate change, and (iii) the carbon footprint of health systems under climate change. Nevertheless, the IPCC (2023) suggests with medium confidence that the economic benefits for human health from air quality improvement arising from mitigation action can be of the same order of magnitude as mitigation costs, and potentially even larger. Furthermore, understanding the impacts of a 1.5°C and 2.0°C warming in a wide range of sectors including the public health (e.g., food distribution, tourism, coastal infrastructure, poverty) and the linkage with human migration is still a major gap in climate-health research especially for developing countries, rural communities, indigenous groups or marginalised people (WHO, 2021, WHO 2018, WHO, 2019).

In terms of policy, understanding the uncertainties and their communication are fundamental in the selection of appropriate adaptation policies for the health sector (Wardekker et al., 2012). Despite the development of numerous adaptation and mitigation measures throughout the EU, the specific objectives related to health often lack robustness (Dickin & Dzebo, 2018). It is essential to integrate health impact evaluations into all proposed initiatives, with monitoring systems that link health and climate data to evaluate the effectiveness of these strategies (Semenza, 2021, Haines et al., 2018). Optimising each initiative requires a system thinking approach to uncover potential synergies (EEA 2017), unplanned consequences (Abel et al., 2018; Hasegawa et al., 2018; Williams et al., 2018), and trade-offs. Likewise, employing system methodologies is essential to ensure adaptation approaches are effective in achieving their goals. Furthermore, formulating science-based policies considering different spatial and temporal scales is still less well-developed for the spatial dimension. There is a need to consider widespread upscaling of actions together with a combination of several strategies specifically adapted to the local scales (Iodice et al., 2024). Addressing the obstacles to action is urgent and requires a renewed commitment to involving and educating citizens about the pressing matters concerning climate change and health (EASAC, 2019). Results of the H2020 project ENBEL highlight the importance of a co-design approach in climate and health research to ensure that adaptation and mitigation strategies are feasible and acceptable among local communities (Lusambili et al., 2023).

SOCIAL JUSTICE. Climate change has already caused widespread negative impacts and related losses and damages to ecosystems and human systems that are unequally distributed across regions and sectors (IPCC, 2023). In the absence of mitigation and adaptation measures, these impacts and associated risks will be amplified in the future in an unmanageable manner for the society. The extent to which current and future generations will experience a hotter and different world depends on choices to be done now and in the near term (IPCC, 2023) implying the addition of a generation justice component to the more general social justice. The climate crisis exacerbates, as already stated above, existing – gendered and intersectional – socio-economic inequalities (World Bank

2019), a situation made worse by the Covid-19 pandemic (Şahin & Erensü, 2020). Climate change is a disaster that unfolds through the destabilisation of ecosystems, alterations in the distribution of settlement, and increases in the occurrence of extreme weather events. Climate change is also a form of slow violence most keenly felt by the poor (Nixon 2013). Moreover, climate change exacerbates regional income disparities in Europe, particularly affecting regions that are already economically disadvantaged (Breil et al., 2018), where southern regions face more severe consequences of climate change, thus widening income disparities across the continent (van Daalen et al., 2024). The above context depends also from the fact the fact that wealthier regions and individuals are better able to invest in adaptation measures, such as flood defences and air conditioning, to protect their assets. In contrast, less wealthy regions and individuals face greater losses due to their limited capacity for such investments (Ciscar et al., 2011).

The challenges in the assessment of climate change impact on the social justice sector are particularly complex. In recent years, the concept of "just transition" has gained traction with reference to meeting climate goals by ensuring the whole of society – all communities, all workers, all social groups – are brought along in the pivot to a net-zero future. Just transition means "Greening the economy in a way that is as fair and inclusive as possible to everyone concerned, creating decent work opportunities and leaving no one behind". This concept is becoming increasingly mentioned in various documents from international organisations and the European Commission, which, among others, established the already mentioned JTF.

Highlighting the choice to focus on the perspective of a socially just transition, representing a combination of climate justice and social justice perspectives (Stevis & Felli, 2016). However, it is not yet very clear how, in practice, we can combine social justice with climate justice in many policies relating, for example, to urban mobility, sustainable food consumption, areas protected, safeguard of human settlements to improve adaptation to climate change. These policies, often, risk to affect the poorest and most disadvantaged people. Preventing/limiting the circulation of the most polluting cars almost always means making mobility more difficult for the poor, while healthy foods often have higher prices or, again, it is the marginalised people who, mostly, live in houses built in areas floodable that should be destroyed (while building renovation according to adaptation and energy efficiency standards increases their cost). At the same time, the poorest and most disadvantaged people, often, are less able to react. For instance, EEA (2019) emphasises that low-income households are less able to invest in protective measures and are more vulnerable to the impacts of climate change, such as increased energy costs due to the transition to renewable energy sources. These are just a few examples that highlight how the dilemma between environmental sustainability and social justice still largely needs to be resolved.

The identified research gaps in the social justice sector could be formalised as below:

- ✓ Theoretical gap - It is appropriate to continue theoretical research to bring greater order between the concepts used and the phenomena to which they refer. E.g. about the interrelationships between social justice and climate justice; between social justice and just transition. Or between vulnerability, inequality and social exclusion in relation to environmental sustainability and climate change (to mention just a few of the current theoretical gaps).
- ✓ Measurement gap - A very important gap concerns measurement. There is no shortage of proposals on how to measure the phenomena that have been discussed so far, but there is a lack of consensus in this regard, both within the scientific community and among policy-makers. It is also for this reason that little has been done to consider social justice in modelling .
- ✓ Social actors' knowledge gap - It has already been highlighted how natural risks have differentiated effects on various social groups, often much greater on some disadvantaged/marginal/poor groups. On these groups, some policies functional to mitigation and/or adaptation relating to climate change can even have negative effects. Since a tailoring of risks and policies is therefore necessary, research must make considerable progress in this regard, first of all to be able to identify and understand the various human groups in the various risk situations.
- ✓ Intersectional gap - The above-mentioned gap is still more deep having in mind that intersectionality broadens the categories and factors included in the analysis and addresses their intersections, which account for the variability of intentional and unintentional, positive and negative rebound effects we observe (Davis 2008; Ritzer & Stepinisky, 2013). So, we have to consider that people can be, at the same time, e.g. woman, migrant and poor; or elder, disabled and geographically isolated; or unemployed, belonging to LGBTQ community and illiterate; etc. (a lot of intersections are possible). An intersectional approach in climate change research is far from

adequate (although important studies already exist - EEA, 2018; Lomborg, 2020) and it is needed for putting, effectively, social justice into the research Agenda.

Under the lens of social justice in relation to natural hazards/risks the main policy-gap is signified by the fact that too little is being done to address inequalities between regions and between social groups, which are exacerbated (among other things) by climate change. In this frame, a specific gap is the lack of tailored policies considering enough the specific situations of disadvantaged people. This is true at main levels: from local risk management plans to national, regional and international mitigation and adaptation policies. It could be noted that some tailored policies exist and are also operational but, at the very least, there is a lack of systemic approach in this regard almost always and almost everywhere, and there is a lack of adequate coordination among the various stakeholders.

EEA (2018) discusses how intersecting income-wealth-gender inequalities require comprehensive policy responses that address the root causes of vulnerability. Effective climate policy in Europe must consider the differential impacts on various social groups and aim to reduce these disparities through targeted interventions. For instance, social protection programmes can be designed to support the most vulnerable populations, including low-income and female-headed households, by providing financial assistance and resources for adaptation.

A related policy-gap is the lack of awareness of this issue (often) among most of the stakeholders (from civil protection to firefighters) officially in charge of risk management in its different phases (preparedness, emergency, and recovery) and at the different levels (from local to international). A further related gap is inherent to communication among social actors/relevant stakeholders on these policies.

MIGRATION. The common expectation is that an increase in average global temperature of 2°C or more above pre-industrial levels would result in substantially higher migration flows in the coming decades. According to Cattaneo & Peri (2016), the main impact of temperature increase is through an effect on agricultural productivity and, hence, countries experiencing larger increases may have suffered declining agricultural productivity. This channel, which should mainly affect rural populations, has differential consequences on emigration rates depending on the income level of potential migrants. Increasing weather and climate extreme events have exposed millions of people to acute food insecurity and reduced water security, with the largest impacts observed in many locations and/or communities in Africa, Asia, Central and South America, LDCs, Small Islands and the Arctic, and for small-scale food producers, low-income households and Indigenous Peoples globally.

Several research gaps related to migration are related to the lack of a set of indicators capturing the interconnectedness between farmers' adaptation and decisions to migrate. Dearth of data on potential migrants, intention-to-migrate, stated versus revealed preferences, reasons for migrating in not filled yet. There is a significant lack of comprehensive data on climate migration patterns, making it challenging to develop evidence-based policies. Improved data collection and research are needed to understand the scope and impact of climate migration. Furthermore, there is no international legal category for climate refugees, and climate change is not grounds for international protection. The 1951 Refugee Convention conditions refugee status on fleeing persecution on one of five grounds—race, religion, nationality, political opinion, or membership in a particular social group—and makes no mention of environmental factors. Theoretically nations could reopen the convention to modify the definition, but the UN High Commissioner for Refugees (UNHCR) and others fear doing so would more likely result in weaker protections for currently recognised refugees rather than expanded grounds for climate refugees, since there is limited political appetite in many countries to expand asylum and resettlement generally (IDMC, 2023).

So far, some global policy instruments have been developed and are currently applied (ICMPD, 2023): In Africa and Latin America, the Organisation for African Unity (OAU) Convention and Cartagena Declaration provide a more expansive refugee definition that includes "people fleeing serious disturbances to public order," which some have taken to include environmental degradation and climate events. In 2010 and 2011, Kenya and Ethiopia gave Somalis fleeing famine and drought protection under the OAU Convention definition. Furthermore, The UN Human Rights Committee found in 2020 that immigrants have a right not to be returned to their places of origin if doing so would pose a risk to their right to life. This ruling has not been used to prevent deportation (the right to life threshold is quite high), but legal provisions in Canada, Italy, the United States, and other countries prevent deporting migrants to countries recently affected by severe disasters (ICMPD, 2023).

Despite such efforts, scientific literature highlights several key policy gaps in Europe regarding climate migration. These gaps reveal critical areas where current policies are insufficient or entirely absent, emphasising the need for a more comprehensive and integrated approach.

FINANCE. Climate-related risks pose a threat to financial stability in Europe. In the "Financial Stability Report", issued in 2023 by the European Central Bank, climate change, along with geopolitical risks and ageing population, are seen as a medium and long-term sovereign debt vulnerability for financial stability. Climate change is a systematic risk to the financial sector, having the potential to upset the system's regular operations and leading to detrimental effects on the actual economy. The physical risks associated with severe weather events and the transition risks related to the policy and technological changes necessary to achieve a greener economy, are two categories of climate-related risks that threaten financial stability. The transition towards a low-carbon economy requires a broad array of financial instruments and innovations that will have far-reaching implications for markets, firms, intermediaries and investors[8].

The World Bank is supporting developing countries to reach their climate goals under the Paris Agreement by its new Climate Change Action Plan (CCAP) based on three umbrella trust funds. These funds aim to influence climate policies, market creation and project design before investments are made (World Bank, 2022).

The International Monetary Fund has an important role in addressing the policy changes posed by climate change and significantly increased its engagement in climate change matters (ECB, 2022).

Banks are encouraging businesses to invest in green technologies by launching different financial instruments. One of these instruments is Green Economy Financing Facilities released by European Bank for Reconstruction and Development (EBRD) that together with co-financing partners avoid almost 9 million tons of CO2 emissions per year. The aim of the (EBRD) is to become a majority green bank by 2025, investing 50% of its portfolio in green projects. The EBRD has committed to fully align its own financial flows with the objectives of the Paris Agreement.

European Central Bank (ECB) set three strategic objectives for climate-related activities: managing climate-related risks, supporting the green transition and fostering wider action (ECB, 2024). In its climate and nature

[8] https://climateimpact.edhec.edu/sustainable-investing

plan 2024-2025, ECB will continue to implement and expand their current climate-related actions and to explore three focus areas in 2024 and 2025. The main achievements are related to incorporation of climate considerations into monetary policy. ECB will focus in 2024-2025 on (i) transition to a green economy, (ii) addressing the increasing physical impact of climate change and (ii) advancing work on nature loss and degradation.

The global financial system will be crucial in channelling capital towards new green assets (mitigation) especially for clean power generation (OECD, 2021). By greening their investment portfolios, investors could, therefore, jointly reduce vulnerability to the consequences of climate change and contribute to the reduction of pollutant emissions.

INSURANCE. Climate change is a global challenge posing material risks to society and the economy. The IPCC has emphasised the importance of risk-sharing and risk-transfer mechanisms for addressing the adverse effects of climate change (IPCC, 2012). In addition, reports released by the United Nations Framework Convention on Climate Change (UNFCCC, 2013) emphasise the significance of insurance in adapting to climate change impacts and addressing the losses and damage that they cause.

In Europe, only around 25% of the overall economic damages brought by extreme weather and climate-related events are now covered by insurance, according to EIOPA[9] (the European Insurance and Occupational Pensions Authority's dashboard on the insurance protection gap for natural catastrophes). The insurers and policy makers are concerned about the pricing of climate-related risks that increases the insurance protection gap.

The literature review of the climate risk insurance research done by Lin et al. (2023) has revealed that most of the studies (86%) were produced in only five countries: U.S.A. (47.7%), China (14.8%), United Kingdom (8.6%), Germany (7.8%) and Netherlands (7.3%). These authors consider that despite the diversification of climate insurance research, the literature is largely dominated by contributions from developed countries. The climate risk insurance research is focused on disparate regions and sectors, conducting to the difficulty to integrate studies over large areas and different sectors. In addition, the large volume of literature covering many

[9] https://www.eiopa.europa.eu/tools-and-data/dashboard-insurance-protection-gap-natural-catastrophes_en

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disciplines hind to assess the temporal evolution of climate risks (Lin et al., 2023).

In the EU Adaptation Strategy (European Comission, 2013), the third objective (O3 Promoting adaptation in key vulnerable sectors) encouraged the use of insurance against natural disasters (Ramboll & IVM, 2017). In the new EU Adaptation Strategy released in 2021, EC promotes the insurance schemes as tools for adaptation to climate change and address the climate protection gap. In addition, as part of the forthcoming Renewed Sustainable Finance Strategy, the Commission will explore further actions in the provision of climate-relevant insurance products. This will include best practices in financial instruments to manage temporary risks, whether market or climate-induced, and the potential of novel and innovative risk transfer solutions. In autumn 2022, EC launched the Climate Resilience Dialogue [10] as a concrete action to reduce the climate protection gap through facilitating exchanges between insurers, reinsurers, public authorities, and other stakeholders. In the Interim Report (2023) [11], the Dialogue group identified the areas where there are gaps (awareness gap, data gap, skills gap, trust gap, etc.) and will include into discussion the EIOPA study "Measures to address the demand side aspects of the NatCat protection gap" (EIOPA, 2023).

As part of the EU strategy on adaptation to climate change, EIOPA has intensified its attention on resolving protection gaps considering the events' increasing severity and intensity. EIOPA adopted several initiatives that aim to make the insurance sector and society more resilient to climate shocks. In this regard, EIOPA studied the solutions to uptake NatCat coverage in Europe for reducing insurance protection gap. The preliminary conclusions showed that in the present there are numerous demand-side factors (e.g.: lack of clarity in terms of costs and coverage, previous negative experience by oneself or within the community, consumers are not aware of the risk in many Member States, high expectations about State intervention) that limit the increase of NatCat coverage uptake (EIOPA, 2024).

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[10] https://climate.ec.europa.eu/eu-action/adaptation-climate-change/climate-resilience-dialogue_en

[11] https://climate.ec.europa.eu/system/files/2023-07/Climate%20Resilience%20Dialogue%20-%20Interim%20Report.pdf

ENERGY. The energy sector is the largest contributor to global green house gas emissions (IPCC, 2014), being responsible for the human-induced warming in the climate system, but it can be vulnerable to the changing climate effects. The widespread application and use, and open data sharing, of advanced weather, water, and climate information and services is essential to deliver climate-resilient energy transition, and effective use of existing energy resources, and the maintenance of energy security at both national and European levels.

The impacts of climate change on the energy sector have been widely studied in the recent decades. All aspects of the broadly defined European energy system are potentially vulnerable to climate change and extreme weather events (Harison et al., 2015). The challenge lies in assessing the impacts resulting from the projected increase in extreme weather events. Current methodologies, based on past experience, may not sufficiently guide planning and operational activities for the coming decades (Viguié et al., 2021). Schaefer et al. (2012) noted that climate impact assessments for energy planning and operation should consider a wider range of scenarios and investigate specific energy segments. When analysing the impact of climate change on energy segments several authors noted the highly dependency of their results with the climate model used as the inputs. Several papers have reviewed the literature on specific energy sectors such as solar energy (Kabir et al., 2018), wind energy (Pryor et al., 2010), hydropower (Chilkoti et al., 2017), bioenergy (Tuck et al., 2006, Berndes, 2003). However, several gaps in the research of climate impact modelling on energy sector can be identified.

Existing research often focuses on a limited range of climate scenarios. To address this gap, future studies should explore a broader spectrum of climate projections to capture a wider range of potential impacts. Also, some regional biases can be identified. Research tends to be biased toward certain regions, leaving gaps in a better understanding of climate impacts on energy system in other areas (Yalew et al., 2020). Tropical regions would face an increase in energy consumption for cooling, while temperate regions would need less energy demand for heating purposes (Schaeffer et al., 2012). Thus, efforts should be made to improve the studies across different geographical contexts. A review study revealed that while there is a broad agreement on the impacts of climate change on wind, solar, and thermal energy sectors, projections for hydropower vary significantly (Cronin et al., 2018). Another gap is that some energy segments have received less attention in climate impact assessments (e.g., bioenergy).

Also, only a few studies on wave power or tidal power energy were analysed. On the contrary, most studies investigating the impact of climate change on the energy system focuses almost exclusively on heating and cooling demand, while overlooking other potential sectors.

Addressing the policy gaps is essential for developing robust strategies to mitigate and adapt to the impacts of climate change on energy systems. One major policy gap is the insufficient integration of climate and energy policies (Markandya et al., 2014). It was identified a significant gap in policies aimed at enhancing the resilience of energy infrastructure to climate e change impacts because the actual policies focus on reducing emissions rather than ensuring that energy systems can withstand extreme weather events, rising sea levels or other related climate hazards (Lin & Wu, 2024). Moreover, many countries have separate strategies for climate mitigation and energy planning, leading to misaligned objectives and inefficiencies. While there has been progress in promoting renewable energy, policies often fall short in providing the necessary support for large-scale adoption and integration into the existing energy grid. This includes financial incentives, regulatory frameworks, and technological support for renewable energy projects (Andersen et al., 2020).

TOURISM. As the natural assets exploiting the climate and landscape features are among the main resources of a destination (Manrai et al., 2018), the physical impacts associated with climate change are likely to influence and possibly reshape the local opportunities for tourism. Each destination type has specific vulnerabilities related to the changes in climate conditions. Coastal destinations are particularly vulnerable to coastal flooding, seawater intrusion and erosion, which undermine their attractiveness and sustainability. Key studies show that Mediterranean areas are particularly threatened, with heritage sites at risk of flooding. Island tourism is also highly susceptible to these impacts. Moreover, rising temperatures and heat stress during the peak summer season may discourage tourists, leading to a potential drop in tourist demand. Tourist destinations that depend on the ski industry, glacier tourism, and winter sports are threatened in the Alps. Indeed, these areas are highly dependent on natural resources and attractions that are highly susceptible to climate change. The impacts of climate change on winter tourism, particularly on snow-dependent activities, are predominantly negative, resulting in shorter seasons and greater variability of snow conditions. Additionally, there is an increased risk of natural hazards such as avalanches and landslides, which can disrupt tourism infrastructure and pose safety risks to tourists and local communities. Furthermore, heritage sites, including UNESCO heritage sites in coastal areas, are at significant risk of flooding, which threatens cultural preservation and tourism. Finally, climate change exacerbates human-wildlife conflict and pressures from human population growth in wildlife areas. The combined effects of these factors threaten the viability of tourism by reducing the attractiveness of natural sites, potentially leading to a decline in tourism activities and associated revenues (Peeters et al., 2024, Steiger et al., 2022, Köberl et al., 2016).

Tourism hospitality industry highly depends on weather, and it develops complex and interrelated relationships with climate. While the immediate profit is very sensitive to the weather conditions, the direct investments to adapting the sector to climate threat are less applied. Tourism is not prepared to face the net-zero transition and climate disruption that will transform tourism over the next decades, and the climate change imperative demands more research focused on climate resilient tourism development (Scott & Gössling, 2022).

Additional challenges are related to the climate change impacts on other sectors related to tourism (e.g., water, energy, transport) which will impose constraints on tourism sector development paths. One example is water scarcity, as tourism significantly increases demand for water during the peak season, creating conflicts with residents and other sectors. In this context, significant challenges for rural tourism are related to green transition as this will require solutions for decreasing energy use and emissions, in buildings and in transport sectors, introducing circular economy models, improving waste and water management (Karin & Sajn, 2023).

Notwithstanding the above achievements, the current research landscape is characterised by significant limitations. One of the most significant challenges is the uneven distribution of research focus across geographical regions. Research is predominantly concentrated in economically developed countries, with limited cross-collaboration between different geographic regions. This excessive concentration of research limits the global understanding of the impact of climate change on tourism and hinders the development of comprehensive and universally applicable strategies. At the national level, the regional focus may not fully capture the broader impacts of climate change on tourism in different geographic areas. Consequently, a significant proportion of national tourism plans, and climate policies lack comprehensive strategies for recognising and responding to climate change risks (Dube, 2024, Scott & Gössling, 2022).

Furthermore, the utilisation of a restricted range of regional climate models (RCMs) and emission scenarios constrains the reliability of the projections. The models frequently rely on the climatic preferences of specific tourism segments, such as young Northern Europeans, which may not accurately reflect the broader tourism population. Also, current analyses focus on traditional sun, sea and sand (3S) tourism, overlooking the growing significance of other forms of tourism, such as cultural and adventure tourism. This narrow focus may underestimate the potential gains in tourism demand during off-peak seasons. Existing studies have mainly focused on certain aspects such as carbon emissions, often neglecting other critical issues such as water scarcity and extreme weather events. The methodologies used are often positivist, with less emphasis on constructivist or critical approaches, which could provide insights into the complex interaction between climate change and tourism. Finally, one of the main limitations is the persistent gap between scientific research and practical implementation. Academic studies frequently fail to address the specific needs of industry stakeholders, resulting in limited real-world impact. Furthermore, the fragmented nature of climate change research in tourism, with a focus on isolated case studies and specific issues, hinders the development of comprehensive and scalable solutions. Consequently, the reliance on traditional methods of knowledge dissemination, such as peer-reviewed publications, limits the accessibility and usability of research findings for practitioners and policymakers. In conclusion, it can be said that the total picture appears incomplete (Pan et al., 2023, Loehr and Becken, 2021, Köberl et al., 2016).

Regarding the modelling of climate change impact for the tourism sector, the prevailing tourism demand models use historical monthly data and regression techniques focusing on the influence on tourism of either (i) year-to-year climate variability or (ii) of intra-annual climatic variations on the seasonality (Köberl et al., 2016). However, the reliability of these models is limited by their dependence on specific emission scenarios, regional climate models and data quality. To enhance the precision of projections, it is essential to develop more comprehensive models that encompass a broader spectrum of scenarios and consider non-climatic factors, such as visitor behaviour and destination characteristics. This would necessitate the incorporation of economic and social variables, in addition to climatic variables, as proposed by Dube (2024) and Köberl et al. (2016). The effective modelling of rural tourism in the context of climate change also necessitates the creation of scenarios that consider the variability of local conditions, infrastructure and resource availability.

To enhance our comprehension of the interrelationship between climate change and tourism, it is imperative to address several research gaps. Firstly, further research needs to be conducted on the effects of climate change on tourism in regions which are underrepresented in the literature, despite their vulnerability to climate change and the growth of their tourism industries. Furthermore, the impact of climate change on sports tourism and ecotourism, and the resilience of the tourism sector to climate change, have not been sufficiently addressed. A significant gap in the current research landscape is also the need for more integrated and interdisciplinary approaches that combine scientific, practical and local knowledge to develop holistic solutions. Research is required to gain a more comprehensive understanding of the socio-economic and socio-political impacts of climate change on different types of tourism and destinations, particularly in vulnerable and tourism-dependent regions. This is with a view to achieving poverty reduction and the equitable distribution of benefits. Moreover, there is a paucity of studies that examine the efficacy of various adaptation and mitigation strategies, as well as the long-term implications of climate change for tourism development and sustainability. Further research is required to gain a deeper understanding of the implications of proposed climate policies on tourism and to develop effective and equitable strategies to manage demand for air transport in the context of zero net emission targets. Moreover, research that considers the full range of weather conditions and potential opportunities and challenges is required. Furthermore, there is a need for improved scientific communication and studies addressing liability and regulatory risks. It is therefore of the utmost importance to address these gaps to develop robust strategies to mitigate and adapt to climate impacts. Further, investigation is required to ascertain tourists' willingness to adapt travel dates and preferences in response to changing climate conditions (Dube, 2024, Scott and Gössling 2022, Steiger et al., 2022, Loehr and Becken, 2021). Finally, there is a missing link between tourism and other related sectors (e.g., transport) with significant contribution to climate change (Peeters et al., 2024). Tourism is underrepresented on the research and policy agenda in relation to the present climate challenges, and the tourism policy and planning are disconnected very likely due to a lack of awareness and non-inclusion (Scott & Gössling, 2022).

The current policies frequently fail to address the specific needs of the tourism industry in the context of climate change, resulting in inconsistent and fragmented approaches. There exists a dearth of comprehensive policies that address the specific needs and vulnerabilities of tourism destinations and consider both the environmental impacts and socio-economic aspects of tourism. Policies also often fail to consider the dynamic nature of tourist behaviour and potential changes in travel patterns due to climate change. Furthermore, existing policies may not sufficiently promote sustainable resource management practices, such as a reduction in greenhouse gas emissions and water management in tourism. This may exacerbate conflicts between tourism demand and local water needs (Peeters et al., 2024, Köberl et al., 2016). Furthermore, existing policies are not adequately addressing the needs of peripheral and less accessible regions. It is also worth mentioning the notable lack of detailed studies examining the content, implementation, and effectiveness of these policies (Pan et al., 2023, Rotich, 2022).

TRANSPORT. Transportation infrastructure, although naturally designed to withstand various hazards, remains susceptible to the increasingly severe natural events induced by climate change, due to their constant intensification. Disruption of this sector, upon which society depends critically, can induce substantial socio-economic losses that extend beyond immediate casualties and physical damage. Extreme weather events, particularly heavy rainfall and floods, are responsible for a significant portion of road maintenance costs in Europe, representing about 10% (0.9 billion euros per year) as for 2012. One of the most critical threats is thought to be the scouring phenomenon, which leads to bridge damaging. River flow projections unveil changes that will amplify scouring in the future.

Climate change is expected to have mixed effects on road maintenance costs in Europe. While more frequent extreme precipitation and floods could increase costs, milder winters might conversely lead to savings. However, rising average temperatures across Europe may necessitate adjustments to maintenance practices, potentially incurring additional costs (European Commission. Joint Research Centre. Institute for Prospective Technological Studies., 2012). Rising temperatures and extended periods of intense heat can alter rail infrastructure, leading to buckling of tracks. Additionally, these conditions can induce pavement deterioration and create thermal discomfort for passengers utilising various transportation modes. In coastal regions, rising sea levels and associated storm surges pose a significant threat to harbours and other transportation infrastructure situated in flood-prone areas such as estuaries and near the seaside (EEA, 2014). Reduced visibility due to fog, dust, sun glare and smog, can produce damages to vehicles, increase risk of collisions, reduce speed and lead to delays (Wang et al., 2020). Climate change induced challenges imply improvements in infrastructure design, planning and maintenance, as well as network and vehicle performance (Wang et al., 2020, Chinowsky et al., 2015, Meyer et al., 2014). Research is scarce in the large public domain as it mainly focuses on specific regions and means of transport (Wang et al., 2020).

BIODIVERSITY AND ECOSYSTEM SERVICES. Climate change is impacting ecosystems by altering species compositions and distribution, species interactions and individuals' growth and development. Species resilience and fitness is reduced due to changing climatic gradients, latitude, altitude and phenology shifts and the projected impact of climate change on different species groups shows alarming percentages of insects, plants and vertebrates that will lose large part of their climatically determined geographic range (Wudu et al., 2023). In this context, many challenges and research needs are related to the assessment of the primary impacts of climate change on biodiversity in Europe, such as: habitat loss and fragmentation, species distribution changes, phenological shifts, exposure to extreme weather events, ocean acidification, disruption of ecosystem services, impacts of the invasive species, genetic diversity loss, human responses to climate change, and the synergistic effects. The challenges and threats posed by climate change to biodiversity in Europe are profound and multi-faceted. Addressing these issues requires comprehensive and integrated conservation strategies, international cooperation, and adaptive management approaches. Protecting Europe's biodiversity in the face of climate change is crucial not only for the natural environment but also for the ecosystem services upon which human societies depend.

Habitat loss and fragmentation. In Europe, temperature and precipitation shifts are leading to significant habitat alterations. The Mediterranean region is particularly vulnerable, with increasing temperatures and decreasing rainfall transforming forests into grasslands and deserts. Coastal habitats are at risk from rising sea levels, threatening unique ecosystems like the salt marshes of the Netherlands and the mangroves along the southern European coasts. Additionally, changes in water availability and seasonality are affecting wetland areas such as those from the Danube floodplain and the Danube Delta.

Altered species distribution. Species across Europe are shifting their ranges northwards or to higher altitudes. For example, the mountain ecosystems in the Alps are experiencing upward shifts of flora and fauna, resulting in increased species competition and altered ecological interactions. Species like the Iberian lynx and certain butterfly species are migrating to cooler areas.

Phenological changes. Climate change is causing significant shifts in the timing of biological events in Europe. Earlier springs are leading to earlier blooming of plants, which may not align with the availability of pollinators like bees. This mismatch can reduce reproductive success and impact food availability for other species, disrupting entire food webs and potentially causing impacts on the different ecosystem services.

Increased frequency and intensity of extreme weather events. Europe is experiencing more frequent and intense extreme weather events, including heatwaves, storms, and droughts. These events can cause immediate and large-scale damage to ecosystems. For instance, the 2019 European heatwave led to severe forest fires in Spain and France, destroying habitats and having a huge impact on biodiversity.

Ocean acidification and warming. The warming and acidification of European seas, particularly the Mediterranean and the North Sea, are affecting marine biodiversity. Coral reefs, such as those in the Mediterranean, are experiencing bleaching events, and the changing ocean chemistry is impacting shellfish and other marine organisms crucial to the food web.

Disruption of ecosystem services. The disruption of ecosystem services in Europe has far-reaching consequences. Changes in pollinator activity are affecting agriculture, with potential declines in crop yields. Alterations in vegetation and microbial communities are impairing soil fertility and water purification processes, impacting both natural ecosystems and human activities.

Invasive species. Climate change is facilitating the spread of invasive species in Europe. Warmer temperatures allow species like the Asian hornet and certain plant species to expand into new areas, outcompeting native species and altering ecosystem dynamics. Disturbed ecosystems are particularly susceptible to these invasions, further threatening native biodiversity.

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Genetic diversity loss. Population declines due to climate change are leading to a loss of genetic diversity in European species. Small, isolated populations, such as those of the Scottish wildcat, face genetic bottlenecks and inbreeding, reducing their ability to adapt to changing conditions and increasing their risk of extinction.

Human responses to climate change. Human responses to climate change, including land use changes and urbanisation, can exacerbate biodiversity loss. For example, the expansion of renewable energy infrastructure like wind farms can lead to habitat destruction. Urban sprawl in response to climate-induced migration also encroaches on natural habitats, further stressing biodiversity.

The synergistic effects. The combined impact of these factors can lead to more severe declines in biodiversity than any single factor alone. For instance, habitat fragmentation combined with climate change can create "climate traps," where species are unable to migrate to suitable habitats, leading to local extinctions.

The impacted biodiversity is affecting the type, quality and quantity of ecosystems services provided to society, and in the end human well-being. Conserving natural ecosystems and restoring the degraded ones is essential and still challenging, as biodiversity plays a crucial role in reducing negative effects of climate change.

Climate change is expected to amplify climate extremes and their impacts on biodiversity and ability of ecosystems to provide services. However, there is no currently standardised approach to mapping ecosystem services that is generally accepted. Ecosystem service mapping studies vary in their approach according to the scale of the study, ecosystem type and ecosystem services provided. The EU Mapping and Assessment of Ecosystems and their Services (MAES)[12] process (Maes 2016) proposes a multi-tiered approach (Grêt-Regamey et al., 2015) with different methods for different levels of detail and complexity depending on data and resource availability (Burkhard and Maes, 2017), the „matrix" approach (Burkhard et al., 2014), linking land cover types to ecosystem service potentials, flows and demands, being the basic, tier 1, rapid assessment of ecosystem services. To inform an ecosystems approach, mapping tools

[12] https://data.jrc.ec.europa.eu/collection/MAES

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need to consider both the environment and society and more complex methods and models, from tier 2 and 3 can be used in addition to tier 1 approach (Burkhard et al., 2018), the biophysical quantification being done by looking at the processes involved in the delivery of each service needed to estimate the supply.

Thonicke et al. (2020) emphasised the challenges in the assessment of these effects which are multifaceted, reflecting the changes in the dimensions of biodiversity, including: genetic diversity, taxonomic diversity, functional diversity, structural diversity and landscape diversity or heterogeneity. Mahecha et al. (2024) identified some significant persistent research gaps in this sector in relation to climate change, which are related to: (i) consideration of all dimensions of biodiversity, (ii) diversity of spatial and temporal scales , (iii) analysis of feedbacks, (iv) analysis of the societal dimensions and systemic risks. Another research gap targets the understanding of how terrestrial ecosystem dynamics feed back into atmospheric variability and how biodiversity modulates these relationships. There is also, a need for future new generation of predictive models, for capturing the complex interactions between atmospheric processes, biodiversity patterns, and ecosystems, under climate change.

Climate change and biodiversity loss are interconnected (CBD, 2017), but policy frameworks often treat them separately as shown by the outcome of the common IPBES-IPCC workshop (Pörtner et al. 2021) which highlighted the necessity for more synergies and better coordination between biodiversity and climate policies. In the last years the EU made a shift from the traditionally `silo approach´ in the policy areas related to climate change, biodiversity and economy with the EGD (EC, 2019) in order to overcome policy fragmentation, but trade-offs still exist, especially when looking at the potential effects on biodiversity of the increasing use of biomaterials (Paleari 2024). The undervaluation of the nature and a low level of consideration of species shifts in current conservation policies (Bednar-Friedl et al., 2022).

FORESTRY. Climate change is profoundly affecting the growth, health, carbon storage capacity, and distribution of forests, leading to considerable implications for forest management practices, emphasising the need for applied research (Bianco & Lo, 2023). Since the Paris Agreement in 2015, forests have received tremendous attention due to its mainly regulating services. Not only it contributes to climate regulation, protection from natural hazards (floods, avalanches, fires) and water and air purification but it also partakes in, probably the most sought function, carbon sequestration. These attributes have assigned to forestry and its related activities a great importance in research and management exploration, aiming at mitigating global climate change impact and enhancing environmental protection. The challenge in understanding the impacts of climate change with regards to forestry, lies not only in collecting data on temperature, precipitation, and other climatic, biotic, and abiotic factors but also in comprehending how these various drivers interact with human activities and between each other. Obviously, as in any system that looks into the natural capital, the uncertainty of models and their resulted projections have shown to be a complex issue in a changing climate, highlighting the need for reliable data about forests, forest dynamics and forest ecosystems in order to provide or even facilitate adaptive management practices that looks into balancing all pillars of sustainability (economic, ecological and social) (Vacek et al., 2023). Nevertheless, it is not about the ability of forests to mitigate climate change, but it is about how climate change and its associated risks affects forest growth, its various disturbances and management practices. Thus, the main challenge is whether the forests can adapt or not to this factual truth, by its own or assisted.

Forestry is a climate sensitive sector facing multifaceted impacts, involving the ecological, economic, and social dimensions. There is still a great challenge to estimate the climate change impacts on forest ecosystems due to the complexity of altered forest growth patterns and species distributions, exposure to pest outbreaks and forest fires, but also to limited knowledge on ecosystem interactions and responses to climate change (Vacek et al., 2023, Herr et al., 2016).

Furthermore, Herr et al. (2016) highlighted the limitations in the estimation of forest net production, with results sparse both spatially and temporally. The large uncertainty in the predictive models and the economic constraints, hindering the implementation of effective adaptation and mitigation strategies are also key challenges in the forest management in the context of climate change, extreme weather events and their associated impacts (Rinaldi & Jonsson, 2020).

In the climate change context, challenges remain for landscape ecologists for representing the dynamics of complex systems with a computer model (Scheller, 2018). The evaluation of the net impacts of climate change on forests is also still limited by the disparate spatio-temporal scales at which the impacts operate (Lawrence et al., 2022). The model forecasts or projections of the effects of climate change on forests is still often not validated (Araujo et al., 2005) and the model ability to forecast the ecological process interactions (i.e., forest fire – insect outbreak interactions both spatially and temporally) and forest productivity is not fully resolved facing reliability concerns however, demographic distribution models (DDMs) have shown that changes in the forest floor conditions, regardless of the type of drivers (anthropic or natural), can amplify macroclimate change impacts on forest biodiversity, limiting light and a balance in temperature (Sanczuk et al., 2023). Additional limitations are related to the capturing of climate change influences on ecological process interactions and their possible links anthropogenic interventions (Keane et al., 2015, Buma & Wessman, 2011). Blanco & Lo (2023) highlighted that the new assessment approaches should be able to link climate change effects to modelling of physiological response of species (i.e., phenology, photosynthesis, respiration) and frequency and severity of ecological disturbances, including those associated or exacerbated by climate change (i.e., fire, drought, insects' outbreaks). The effects of such processes on some important forest ecosystem processes (i.e., tree growth, biodiversity, competition at ecosystem level) needs to be considered for advancing the current methodological assessment and modelling frameworks. Daigneault et al. (2022) highlighted some persistent limitations related to the incorporation of forest productivity and ecosystem resilience impacts under the different RCPs and the more explicitly accounting of land use change that results from forest conversions.

Further steps to provide quantitative projections of the direct and indirect climate change impacts on forestry (i.e., through impacts on water resources, ecosystem services, land surface conditions; exposure to extreme weather events) (Chou et al., 2016) are still needed. Such further efforts shall facilitate a better understanding of the economic system response to climate change on long-term, in support of adaptation planning and effective forest management (Keenan, 2015). An improved understanding the complex factors contributing to deforestation are also essential for informing policy and decision-making aimed at reducing its impacts (Prochazka et al., 2023). Tackling the drought-increased mortality shall be addressed in all forest types, especially in boreal, temperate and tropical forests as it hinders the ability to store carbon. Since there is less and less information on remote areas, tropical microbiomes and forests on permafrost, targeting exploration in these under sampled locations should be taken into consideration in the future. Considering ecosystem processes, the exploration of the relation between ectomycorrhizal species, species diversity and productivity must be explored further with a deep focus other nutrients cycle, not only carbon. The nutrients cycle in the soil and soil itself is highly understudied, especial in terms of microbial processes and its related communities as it contributes to weathering and carbon capture in organo-mineral complexes (Baldrian et al., 2023). A closer collaboration with the IAM community is needed for coordinated efforts for comparing the forest-specific outcomes of mitigation and adaptation policies across various forest sector modelling frameworks (Daigneault et al., 2022). Other research gaps are associated to the need of intensified efforts for regional comparisons and improvements of methods for downscaling global narratives and forest sector projections to local scales to foster adaptation at sectoral level. It is also worth mentioning that co-design has been increasingly recognised as a valuable approach in various fields and sectors with a great potential to support forest policy (i.e., for natural resource management), there is still a need for its application and integration of its outcomes for sector policy design (Ambrose-Oji et al., 2023).

Further collaborative efforts among the research community, policymakers, forest managers, and local communities is needed to develop comprehensive strategies for climate change adaptation and sustainable forest management. The policy gaps identified in forestry in relation to the assessment of climate change impacts of climate change are related to:

- ✓ Limited uptake, use or translation of science-based knowledge into actionable forest and climate policy and decision-making (i.e., forest management policy), including climate projections (Westwood et al., 2023, IPCC, 2019, Korosuo et al., 2023) and the future climate change mitigation and adaptation implications in the forest management decisions (Korosuo et al., 2023);
- ✓ Limited consideration of future socio-economic impacts on the forest-dependent communities (Prochazka et al., 2023);
- ✓ Limited consideration of carbon fluxes and forest carbon stocks from managed forests systems (Harris et al., 2021, Popp et al., 2017, Forsell et al., 2016; another key related gap foresees the role of timber demand on carbon flux, the influence of climate change policies on forest management and timber production, and the regional variation in carbon and wood product harvest outcomes (Daigneault et al., 2022);
- ✓ Fragmented governance and limited stakeholder engagement due to the existing mosaic of actors and interests influencing forest policies (Horwarth et al., 2022, Wamsler et al., 2021, Ongolo 2015); this

gap is important in the context in which some actors could play an essential role in knowledge transfer and policy design (participatory through co-design) through their valuable knowledge from the corresponding side of the science-policy interface (Westwood et al., 2023).

- ✓ Lack of linguistic clarity and common terminology related to knowledge of climate and forests (Priebe et al., 2023).

As participatory governance often lacks clarity, there is a high request for conflicts mitigation in environmental and social advantages of using wood and its related assortments, stressing the fact that social acceptance plays a key role in shaping woody forest bioeconomy. Certification schemes in small-scale bioeconomy chains is also a modern concern as small private forest owners see this instrument as economically inconvenient thus, future research and approaches should promote this key contributor in environmental and social sustainability (Di Letizia et al., 2023).

AGRICULTURE AND FOOD SECURITY. Climate change is a significant threat to the agriculture and food security sector. It poses major challenges to the global food system, affecting food production, food security, and rural livelihoods (Iizumi et al., 2014, Lobell et al., 2013). Key challenges include changes in temperature and precipitation, which can reduce crop growth and yields. Climate change also increases the severity of extreme weather events, such as droughts, floods, and storms, leading to crop failures, soil erosion, and water scarcity (Iizumi et al., 2014). Simulations suggest droughts could decrease global crop production by up to 20% by century's end. Additionally, shifts in temperature and precipitation can alter the distribution and severity of pests and diseases, further impacting crop yields. For instance, increased occurrences of diseases like wheat stripe rust could threaten food security and rural livelihoods.

Enhancing the resilience of agricultural production systems to climate change requires more efficient use of natural resources and agricultural inputs. Agricultural growth and adaptation are priorities, particularly for poor farmers who are most affected by climate change despite contributing the least to it. To combat these challenges, both short-term and long-term strategies are necessary. Suggested climate adaptation strategies include changes in cropping systems, improved irrigation and soil management, and developing new crop varieties resistant to heat, drought, and pests. Changes in cropping systems, such as crop rotations and intercropping, can enhance agricultural resilience to climate change, while new crop varieties can help mitigate negative effects on food security and rural communities (Ewert et al., 2015, Hertel et al., 2010). Mitigation efforts can provide co-benefits for food security and adaptation, although these may involve additional costs. Climate change and food security entail multiple interrelated risks and uncertainties for societies and ecosystems. Increasing agricultural productivity and incomes in the smallholder production sector is crucial for reducing poverty and achieving food security, driving economic transformation and growth. Developing environmentally friendly, economical, and socially acceptable biotechnologies can help mitigate the impact of global climate change on food security.

Agricultural decision-makers in developing countries face challenges in accessing accurate and up-to-date information crucial for policy and investment decisions affecting food security. This includes data on crop distribution, expected yields, and average plot sizes, which can be expensive to collect and often outdated or incomplete.

Good monitoring is crucial for sustainable ecological management, species recovery, and environmental reporting, especially in response to climate change and increased human activity. It serves various purposes, including understanding system operations, raising awareness, engaging the public, and identifying threats or opportunities. Recent advancements in remote sensing technologies, such as drones and high-resolution satellite imagery, along with improved data processing and machine learning, offer promising solutions to revolutionise the cost, resolution, and accuracy of agricultural data collection. However, the application and sustainability of these technologies can be challenging. Remote sensing transcends earthly limitations, capturing data across various scales and resolutions for diverse applications. Precise crop condition monitoring requires identifying optimal baseline and remote sensing products at resolutions that minimise uncertainties, particularly in the face of fluctuating weather conditions affecting crops (Quian et al., 2019).

Effective techniques for data integration are crucial for creating models that accurately represent the complexity of these systems. However, three main technological challenges have been identified in ecological informatics (Han et al., 2024):

- Data dispersion - refers to the challenge of managing data collected from thousands of sites worldwide, often by independent researchers.

- Heterogeneity - arises from the diverse themes and experimental techniques used in ecological research, complicating data analysis.
- The origins and history of data, is essential for understanding complex results obtained through multistep data collection and analysis processes in ecological research.

Addressing these challenges is critical for advancing our understanding of ecosystems and climate.

Some of the key challenges in the quantification of climate change impacts in this sector are related to: the great variability of crop yields (Rezaei et al., 2023), exposure to pests and diseases of crops and crop resistance to these threats (Dubois et al., 2024), but also to the technological and knowledge gaps for developing resilient crops (Acevedo et al., 2020), financial constraints to implement effective adaptation measures (Kundu et al., 2024), limited coordination between the key stakeholders (Maryono et al., 2024) and food price volatility (Mustafa et al., 2023). Assessing the impacts of climate change on agriculture and food security is a complex task with several limitations, emerging from various factors, including the complexity of agricultural systems and climate-related risks (Rosenzweig et al., 2013), uncertainty in climate and crop models (Luo et al., 2022), and economic shifts and dynamics of economic resources for adaptation (Porfirio et al., 2018).

Despite its many advantages, remote sensing for crop production forecasting still faces several challenges and limitations. Remote sensing data can be affected by atmospheric and other factors, such as cloud cover, haze, and shadows, which can reduce its accuracy and reliability. Remote sensing requires specialised knowledge and skills to interpret and analyse the data, which may not be available to all farmers and stakeholders.

Some persistent gaps in the agriculture and food security sector are related to the estimation of changes in the impacts induced by recurrent and concurrent large-scale extreme events that have a great potential in destabilising the global production system and markets on long-term (Hristov et al., 2023). More research is needed to understand the long-term impacts of climate change on the agricultural sector and uncertainty in the assessment of nature of macro-economic impacts of climate change and their severity.

For this sector, it is also essential to understand the impact of variations in air temperature, CO2, and ozone on corps and their implications for crop production (Hatfield et al., 2011), that is critical for developing cropping systems resilient to stresses induced by climate change (European Commission. Joint Research Centre., 2020). Estimation of the dynamics of food markets in line to the expected future climate evolution is also a need, to empower the farmers with improved knowledge and new options to adapt their practices (Unver et al., 2020). The influence of some limiting factors (not fully integrated into the modelling systems) such as water shortage, constraints on the expansion of irrigation, increasing impacts of heat waves and droughts, consequences of reduction of nutrient use due to environmental and climate mitigation constraints requires additional research and modelling improvement efforts (European Commission. Joint Research Centre, 2020).

The integration of biophysical (i.e., change in air temperature and precipitation, climate extreme events) and socioeconomic (i.e., changes in policy decisions, market prices) factors in assessment frameworks is still a significant challenge. These factors are involved in the exacerbation of climate change impacts and their complex interactions could provide valuable insights for assessing the socio-economic losses and damages from climate change in most sectors (i.e., Rising et al., 2022, OECD, 2021). More research is needed to understand negative macro-economic impacts of climate change on agriculture sector, their severity (Bosello et al., 2020), the sources of uncertainty in their estimates and the regional differences (Orlov et al., 2021, Fernando et al., 2021).

There is a significant lack of systematic tools and approaches for measuring climate change adaptation at various spatial scales, which hinders tracking progress toward the adaptation goals of the Paris Agreement. Current adaptation measurement systems are deficient in being:

- ✓ Coherent: Directly measuring adaptation itself.
- ✓ Comparable: Allowing for comparisons across different geographies and systems.
- ✓ Comprehensive: Supported by necessary data.

Additionally, many adaptation measurement efforts do not have an appropriate counterfactual baseline, which is crucial for assessing the effectiveness of adaptation interventions. To address these gaps, a "Biomass Climate Adaptation Index" (Biomass CAI) is being developed specifically for agricultural systems. This index aims to measure climate adaptation progress across multiple scales using satellite remote sensing. The Biomass CAI can be applied at global, national, landscape, and farm levels to monitor agricultural biomass productivity linked to adaptation interventions. It supports decision-making for end-users, promoting effective climate change adaptation investments and interventions in agricultural and food systems (Ferguson et al., 2022).

The food security literature has significant gaps that limit our understanding and hinder effective policy and practice (Azmi et al., 2023). These gaps include:

- ✓ Inadequate attention to key issues: Certain critical topics, such as food waste and food sovereignty, are underexplored.
- ✓ Limited exploration of intersections: There is insufficient research on how food security intersects with other global issues.
- ✓ Marginalised perspectives: The experiences and perspectives of marginalised groups are often overlooked.
- ✓ Policy implications: There is a lack of focus on the implications of research for policy-making.
- ✓ Standardised methods: Methods for measuring and assessing food security are not standardised.

Addressing these gaps is crucial for sustainable development, given the fundamental role of food security in social, economic, and environmental well-being. To achieve this, researchers, policymakers, and practitioners must collaborate to:

- ✓ Incorporate diverse perspectives into food security research.
- ✓ Prioritise research on understudied issues and their intersections with other global challenges.
- ✓ Strengthen partnerships and collaborations.
- ✓ Improve data collection and analysis methods to capture the complexity of food security issues.

The UN's Convention to Combat Desertification (UNCCD) is one of the three Rio Conventions, agreed at the Earth Summit in Rio de Janeiro in June 1992. Its remit extends beyond desertification narrowly defined to encompass international action, advocacy and policy development on issues related to land degradation, food security and agriculture. Its flagship publication, the Global Land Outlook, is produced on a five year cycle, most recently in April 2022. Its Summary for Decision Makers makes clear, for example, how little European nations have committed to land restoration targets under the Bonn Challenge.

In Europe and beyond, Agriculture is facing significant challenges in balancing productivity with environmental protection and addressing rapid population growth and urbanisation. Agricultural product consumption contributes to climate change and environmental risks, with agriculture being a major source of these impacts. By 2050, if current practices continue, pollution and resource use from agriculture are expected to worsen globally. Reducing the environmental pressures of agriculture is central to the United Nations 2030 Agenda for Sustainable Development, particularly in achieving Sustainable Development Goals (SDGs) related to food security (SDG2), climate action (SDG13), and biodiversity (SDG15). Policymakers need scientific evidence to design strategies that promote sustainable agricultural productivity, climate change mitigation, adaptation, and resource management while ensuring the agricultural sector remains viable and competitive, providing adequate incomes for farmers. Over the past decade, life cycle assessment (LCA) has become a key tool in academia and policy for evaluating and communicating the environmental impacts of agricultural and food systems. LCA helps identify necessary interventions to reduce environmental impacts and supports monitoring progress towards SDGs.

A variety of policy options and market incentives are available to implement environmentally friendly interventions targeting food demand and supply. These include (Gava et al., 2020):

- ✓ Market Incentives: Encouraging farmers to adopt environmental certifications and labeling schemes that grant premium prices, integrating supply-side and demand-side interventions.
- ✓ Policies: Typically focused on regulating primary production. For instance, the EU's Common Agricultural Policy (CAP) supports low-impact farming through mandatory and voluntary instruments like "greening" payments, agri-environment-climate measures, and cross-compliance under the direct payment pillar. The post-2020 CAP reform aims for greater farmer involvement in climate change mitigation and sustainable food provision while maintaining production efficiency.
- ✓ Renewable Energy: Promoting renewable energy standards has encouraged distributed energy models in rural areas, increasing bioenergy use. Public policy frameworks provide investment incentives for farm-based or collective waste-to-energy and waste-to-fertiliser plants.
- ✓ Public Acceptance and Awareness: Focusing on public acceptability of new dietary guidelines, alternative livestock management practices, improved labeling communication, and

consumer education campaigns to raise awareness and responsibility.

- ✓ Evidence-Based Policy: Requires updated information from comprehensive impact assessments and scenario analyses to reduce uncertainties and avoid trade-offs in policy design. This is critical for food policy, often hindered by information failure.
- ✓ System Thinking Approach: Conceptualising interventions using a system thinking approach can address multiple sustainability dimensions simultaneously, fostering synergies among supply chains and stakeholders. It emphasises attention to intermediate supply chain steps and social acceptability of interventions.
- ✓ Stakeholder Communication and Collaboration: Essential for the success of system-level interventions. Policymakers can facilitate connections among stakeholders and enhance product acceptability through educational services, such as those funded by the EU's CAP or the European Innovation Partnership.

Further research is needed to provide evidence from existing system-level approaches, highlight their impact-mitigating potential, observe rebound effects, and identify drivers and barriers to effective interventions. Special attention should be given to countries with significant population and urbanisation growth for effective policymaking towards global agricultural sustainability and food security.

Food sovereignty has the potential to challenge the dominant global food system paradigm and promote more equitable and sustainable food production and distribution. It emphasises the rights of people to define and control their food systems and to produce and consume food that is culturally appropriate, environmentally sustainable, and socially just. By prioritising the perspectives and needs of small-scale farmers and marginalised communities, food sovereignty can address the root causes of food insecurity and foster sustainable and equitable food systems (Amzi et al., 2023). Key points include:

- ✓ Intersection with global issues: The intersections between food security and other global issues like gender inequality, environmental sustainability, and animal welfare are underexplored. For instance, the gendered dimensions of food insecurity are often overlooked, despite women and girls being disproportionately affected. Addressing gender inequality, such as promoting women's land rights and improving access to

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education and resources, is crucial for achieving food security and reducing poverty.

- ✓ Policy implications: The limited focus on translating research findings into policy recommendations can hinder effective interventions. Without clear policy guidance, efforts to address food insecurity may be less effective or inefficient.
- ✓ Standardised methods: The lack of standardised methods for measuring and assessing food security limits the comparability and generalisability of findings. Developing and implementing standardised methods and indicators is necessary for better monitoring and evaluation of interventions on a global scale.

To address these gaps, there needs to be greater collaboration between researchers, policymakers, and practitioners to ensure research findings inform effective policies and programs. Additionally, the development of standardised methods for assessing food security is essential to improve the comparability of findings and enhance the effectiveness of interventions. By addressing these critical gaps, efforts to combat food insecurity can be more comprehensive and impactful, leading to a more just and equitable food system that ensures access to nutritious and culturally appropriate food for all.

WATER MANAGEMENT. Climate change is a critical issue with extensive effects on the environment, societies, and the economy. One of the most concerning areas impacted by climate change is water resources, which are essential for human well-being, economic development, and ecological health.

Currently, it is estimated that approximately half of the world's ~8 billion people face severe water scarcity for at least part of the year due to a combination of climatic and non-climatic factors. Since the 1970s, 44% of all disaster events have been related to flooding. Consequently, a significant portion of adaptation interventions (~60%) are aimed at addressing water-related hazards (IPCC, 2023).

Climate change significantly impacts water resources in terms of quality, variability, and availability (WAREG, 2023):

- ✓ Quality: Rising temperatures increase the growth of harmful algae and bacteria, producing toxins that affect humans, animals, and ecosystems. Natural disasters like hurricanes and floods can wash pollutants into water sources, contaminating drinking water and harming aquatic species.

- ✓ Variability: Changes in temperature and precipitation patterns make water resources increasingly unpredictable. This challenges water managers in balancing the needs of various users, such as farmers and cities, and complicates planning and implementing critical water infrastructure projects like dams and reservoirs.
- ✓ Availability: Rising sea levels and melting glaciers shift water availability, with saltwater intrusion into coastal aquifers limiting freshwater access for local communities. Diminishing water reserves in mountainous regions increase water scarcity, complicating water management efforts and making it harder to meet the needs of all users. Furthermore, more frequent droughts and heat waves will lead to water scarcity (Cotera et al., 2023).

Addressing these impacts requires a comprehensive approach involving collaboration among governments, industry, and citizens to develop and implement effective adaptation and mitigation strategies. A significant portion of adaptation interventions (~60%) are designed in response to water-related hazards and include measures such as irrigation, rainwater harvesting, and soil moisture conservation (IPCC, 2023).

Adaptation strategies for water resource management in a changing climate are vital for ensuring sustainability and resilience. These strategies involve several key interventions:

- ✓ Improving Water System Resilience: Implementing better water management practices like conservation, reuse, and water-saving technologies can sustainably utilise water resources and mitigate droughts and floods. Developing new infrastructure such as dams and treatment plants can enhance reliability and sustainability.
- ✓ Investing in New Infrastructure: Investment in water treatment plants, distribution networks, and storage facilities can enhance water quality and availability, while new sources like desalination plants and water harvesting systems can combat water scarcity.
- ✓ Reducing Community Vulnerability: Communities with limited resources are often most vulnerable to climate change impacts. Adaptation efforts should focus on reducing vulnerability through infrastructure investment, education, and technology adoption.
- ✓ Improving Water Management Practices: Effective water management, including conservation and stakeholder-driven

planning, is essential for resilience. Strategies must account for climate change impacts and stakeholder needs.

- ✓ Encouraging Collaboration: Collaboration between government, industry, and the public is crucial. Through partnerships, effective adaptation strategies can be identified, implemented, and promoted through education and awareness initiatives.

In addition to adaptation strategies, mitigation efforts like reducing greenhouse gas emissions and improving energy efficiency can slow climate change's pace. These efforts can decrease water demand, improve supply sustainability, and reduce climate-related risks. An integrated approach combining both adaptation and mitigation strategies is necessary for ensuring water resource sustainability and resilience in the face of climate change.

Water management is essential for achieving SDGs and facilitating climate-resilient development. However, many mitigation measures have a high-water footprint, which can compromise both SDGs and adaptation outcomes. Water is prominently featured in the nationally determined contributions (NDCs) and national adaptation plans (NAPs) of most countries, as SDGs cannot be achieved without adequate and safe water (IPCC, 2023).

Many mitigation measures, such as carbon capture and storage, bioenergy, and afforestation, have a high water footprint. It is crucial to manage the water intensity of these measures in socially and politically acceptable ways to enhance synergies with SDGs, improve water security, and minimise trade-offs with adaptation.

Climate change presents significant challenges for water management in European countries. Climate change is expected to bring more frequent and intense droughts and floods across Europe. Water managers struggle to balance storing excess water during wet periods to meet the demands of drier periods (IPCC 2007). Predicted changes in rainfall patterns, with some regions becoming drier and others wetter, will render historical water management plans based on averages obsolete (Brown, 2011). Also, existing water infrastructure, like dams and reservoirs, may not be able to handle the fluctuations in water flow brought on by climate change. Upgrading this infrastructure will require significant investment and time. These limitations highlight the need for innovative solutions in water management practices.

Socio-political barriers, including insufficient stakeholder involvement and policy fragmentation, can hinder the implementation of adaptation measures (EC, 2021).

Water adaptation measures generally result in positive economic outcomes. However, a significant knowledge gap remains regarding whether these adaptation benefits effectively translate to reduced climate risks (IPCC, 2023). A comprehensive list of research gaps includes:

- ✓ A need for long-term studies assessing the effectiveness of current water adaptation measures under various climate scenarios (Bartlett and Dedekorkut-Howes, 2023).
- ✓ Many existing adaptation measures are designed for broad geographic areas. Research is needed to develop context-specific solutions that consider regional climate projections, infrastructure capabilities, and social factors (Salerno, 2017). There is also the need to understand the local impacts of adaptation strategies (European Commission, 2021)
- ✓ A gap exists in understanding how water adaptation measures can be effectively integrated with other sectors like agriculture, energy, and urban planning to achieve maximum benefits (UN Water, 2010).
- ✓ Research is needed to explore the social and economic implications of water adaptation measures, including impacts on vulnerable communities and the potential for equitable water allocation during periods of scarcity (Bartlett and Dedekorkut-Howes, 2023).
- ✓ More research is needed to optimise the use of natural ecosystems for water management (e.g., wetland restoration) in different climatic and geographic settings (UNESCO World Water Assessment Programme, 2018).
- ✓ A gap exists in comprehensively evaluating the economic viability of different water adaptation measures, considering both costs and long-term benefits (Salerno, 2017).
- ✓ Research is needed to develop sustainable financing mechanisms for implementing and maintaining water adaptation measures, particularly in developing countries (UN Water, 2010).
- ✓ Research focusing on integrated impacts of climate change on water resources, food security and ecosystem services is also urgently needed (EC, 2021).

Policy gaps in water management in the context of climate change and associated its impacts are related to:

- ✓ The growing complexity of challenges facing urban water management, such as climate change, urbanisation and environmental degradation, warrants a transformative shift away from prevailing siloed approaches of water supply, sanitation and drainage to more integrated systems that enhance adaptive capacity (IPCC, 2023).
- ✓ Current policies might promote generic adaptation measures that don't account for regional variations in climate impacts, infrastructure, and social contexts. Water adaptation policies are sometimes not well-coordinated with other sectors like agriculture, energy, and urban planning. This can lead to missed opportunities for integrated solutions. Evidence shows policies donot adequately address the social and economic implications of water scarcity, potentially disproportionately impacting vulnerable communities (Intergovernmental Panel On Climate Change (Ipcc), 2023) and failing to ensure equitable water allocation during droughts.
- ✓ The importance of fully integrating climate change considerations into long-term planning and management is underscored by persistent policy gaps in the coordination and implementation of climate change adaptation and mitigation strategies (Valencia Cotera et al., 2023) .
- ✓ Moreover, policy gaps are evident in the integration of climate adaptation measures into national and regional water management strategies, highlighting the necessity for policies that promote the implementation of IWRM and NBS (Cotera et al., 2023).
- ✓ Stakeholder participation and the translation of scientific knowledge into workable regulations are crucial, as are measures to ensure equitable distribution of water resources and strengthen the resilience of vulnerable communities (EC, 2021).

2.4. Current progress in biogeophysical, socio-economic, and adaptation modelling

2.4.1. Biogeophysical modelling

BGP modelling aims to understand, predict, and mitigate the impacts of biophysical hazards at different geographical scales, particularly those exacerbated by climate change (i.e., extreme heat, floods, storms, and drought events). BGP modelling also contributes to filling data gaps in the fields or sectors where information is not readily available.

BGP-related hazards affect a wide range of sectors which are altering human well-being and economic stability. While BGP modelling has made consistent steps towards a better understanding and prediction of climate change impacts in different sectors, there are still persistent knowledge gaps, limitations, and challenges. The outputs of various BGP modelling frameworks have been used in various sectors for addressing a wide range of impacts i.e., agriculture (i.e., crop yield, land use change), biodiversity and ecosystem services (i.e., species phenological changes, shifts in primary ecosystem productivity), forestry (i.e., forest productivity, carbon stocks), health (i.e., changes in morbidity and mortality associated with extreme weather events) and water resources (i.e., inland flooding, and water supply and demand). The need for a more efficient translation of biophysical impacts into economic damages for decision-makers paved the way for developing coupled physical-economic modelling frameworks for optimising the policy response to climate change (Piontek et al., 2021, Monier et al., 2018). Piontek et al. (2021) further emphasised that BGP model outputs can be successfully used as the independent variables for estimating micro- and macroeconomic econometric models. Moreover, these models have a great potential for both improving the predictability of economic models and avoiding the parameterisation of the biophysical relationships.

High-resolution climate modelling and climate scenarios are critically important for the provision of actionable knowledge to support adaptation decision-making. Existing and emerging evidence on the accrual of climate related risks with increasing global warming at regional and national levels can inform decision makers about the levels of risk they may face if we do not meet the goals of the Paris Agreement, and the potential requirements for adaptation strategies. However, at more local levels to understand risk in detail it is important to combine hazard data with more localised data on exposure and vulnerability, including sensitivity and adaptive capacity, which remains challenging (Warren et al., 2022).

Many tools exist that provide access to outputs from biogeophysical models. The IPCC AR6 Interactive Atlas[13] provides changes in climate-related hazards which are key drivers when exploring BGP risks. Climate Analytics provides an online Climate Impact Explorer Tool which provides access to modelled data for consistent climate scenarios, including economic damage from fluvial floods and tropical cyclones; population and land exposed to crop failures, heat waves and wildfires; and changes in crop yields. The metrics from Climate Analytics are based on data from the global databases ISIMIP (The Inter-Sectoral Impact Model Intercomparison Project) for biophysical system and extreme event metrics, and CLIMADA (CLIMateADAptation) for direct damage metrics. Importantly, these metrics do not consider socio-economic change, assuming population and GDP remain fixed, and assume no additional adaptation. The Tyndall Searchable Inventory of Global Climate Impacts allows decision makers to search across 29 climate-related risk indicators and 68 metrics to explore climate impacts to 176 countries, projected to occur for global warming of 1.5°C to 4°C above pre-industrial levels[14].

Yet, there is still a lack of comprehensive synthesis of evidence on climate policy co-benefits (Karlsson, 2020) and need for further research for designing policies that can mitigate the impacts of natural hazards on economy and society more effectively (Botzen et al., 2019). In this context, persistent gaps are associated with the need for more accurate socio-economic analyses, as required for the integration of consistent and harmonised scenarios, with improved sectorial and cross-sectorial impact projections at local scale (high resolution modelling and scenarios) (i.e., COACCH project) and economic valuations of physical impacts (i.e., PESETA project - , Christensen & Ciscar, 2012).

Further research is also needed to build an evidence base through climate risk assessments, and provide actionable policy insights, from an improved understanding of extreme climate change pathways and enhanced representation of adaptation in different climate and socio-economic

[13] https://interactive-atlas.ipcc.ch/

[14] (available at: Climate services for a Net Zero resilient world (CS-N0W): overview - GOV.UK (www.gov.uk)

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scenarios. Indeed, a key research priority remains the need to better integrate adaptation into regional and national climate change risk assessments (Berrang-Ford et al., 2021). These efforts could also target the incorporation of climate tipping points and extreme climate shocks (i.e., heat waves, storms, droughts) into economic evaluations through interdisciplinary approaches that bridge climate science, economics and modelling initiatives.

Within the modelling protocol (section 3.2) climate and BGP will be consistent with a range of global warming levels (in increments from 1.5 to 4°C) above pre-industrial levels (current global temperatures are ~1.3°C above the pre-industrial period). Presenting results aligned to defined warming levels allows climate hazards and BGP risks to be considered in a policy-relevant manner, aligned to regional, national and international targets. Considering an upper range of 4°C also encourages thinking of what such a world would look like, enabling more extreme climate shocks to be modelled, exploration of what this means for adaptation planning, and to support stress testing of economic systems via economic models.

The integration of agent-based modelling and tailored causal loops in a complex adaptive system-based framework was found to enhance the predictive capabilities in the modelling of health impacts of climate change (Talukder et al., 2024). This framework has been successfully implemented into six health-related systems (ecological services, extreme weather, infectious diseases, food security, disaster risk management, and clinical public health) and provided valuable inputs for the assessment of health impacts associated with climate change and insights into effective short and long-term health strategies under the current and future challenges.

Modelling efforts in the forestry sector are striving to address climate change, which is a major driver of many environmental-related forest changes, for provisioning an improved understanding of how the complex forest and ecosystem systems behave under changing or unknown climate conditions (Machado Nunes Romeiro et al., 2022, Maréchaux et al., 2021). In such a context, forest models are vital instruments in forest research, management, and governance, and they are currently undergoing significant transformation through the integration of new methods to acquire large amounts of input data and refinements in modelling allowing the ingestion of higher levels and complex ecological information at various spatial and temporal scales. However, there is still a limited availability and ability of forest models to link climate change with ecological disturbances (Machado Nunes Romeiro et al., 2022), whereas the regeneration algorithms of these models do not adequately capture the effects of climate change (Hanbury-Brown et al., 2022). Daigneault et al. (2022) underlined that future IAM-based climate policy assessments could contribute to the achievement of a better representation of forest product markets and management dynamics. The climate change impact assessment frameworks in forestry are still subject to important uncertainties. These are mostly associated with lack of standardisation of modelling approaches, effective validation protocols and limitations in the capabilities of allometric models (Blanco and Lo, 2023). These are important sources of uncertainty which limits the accuracy and reliability of forest-climate predictions and forest landscape scenarios. Further effort for achieving a general agreement between forest models on regional forest area and carbon stock trends could help policymakers prioritise regional forest planting, preservation, and management programs in climate mitigation strategies (Daigneault et al., 2022).

Researchers use various modelling tools and techniques to understand and address the impacts of climate change in the agriculture sector. Climate models play a crucial role in projecting changes in temperature, precipitation, sea level rise, and extreme weather events, as well as their effects on sectors like agriculture, forestry, water resources, and human health. In this sector, the contributions of the BGP modelling to the understanding of the socio-economic impacts of climate change are currently not fully effective due to the current limitations in estimating the impacts on biophysical productivity stocks. The current modelling frameworks have a particular focus on the evaluation of the long-term changes in average conditions yield impacts and are limited in estimating the effects of interplay (spill-over) of climate change impacts and expected agricultural market adjustments and competitiveness (Zia et al., 2022). Modlling challenges remain due to data limitations and uncertainties in model outputs, which hinder effective decision-making. Therefore, ongoing research and collaboration are essential to improve the accuracy and reliability of climate models in addressing the urgent issue of climate change.

Biophysical models are valuable tools in estimating species' responses to climate change and well-suited for predicting the associated impacts. Through utilisation of databases of species traits, the modelling approach could be integrated in the biodiversity sector for evaluating and developing adaptation strategies available to conservationists, managers and policy-makers (Briscoe et al., 2022). Numerous studies examined the synergistic effects of land use and climate change on various species (Brodie, 2016, Brambilla et al., 2016). More recent contributions in advancing the assessment of the biophysical and socio-economic impacts of climate change on biodiversity relied on the implementation of integrated modelling frameworks allowing the comparison of the direct biophysical and indirect socio-economic impacts associated to climate change on the distribution and extent of different special at regional scales (Leclere et al., 2020, Powers and Jetz, 2019, Newbold, 2018).

As climate change poses a substantial challenge to urban water management, is further refinement of urban climate models, downscaling and correction methods are needed as also emphasised by the IPCC (Intergovernmental Panel On Climate Change (Ipcc), 2023). IPCC mentions that the quantitative predictions of future adaptation hinge on the availability of ´impact models´ capable of assessing the effects of specific adaptation measures. However, a significant constraint arises from the inability to incorporate all potential future adaptation responses into climate impact models. This limitation restricts the comprehensive evaluation of available options for the future. For instance, certain frequently implemented measures known to yield positive outcomes, such as behavioural and capacity-building initiatives, or migration and off-farm diversification, are often not integrated into quantitative climate impact projection models. Moreover, future adaptation projections rely on existing technologies and approaches, yet new methods and technologies are expected to emerge. Thus, there remains a notable knowledge gap in enhancing the representation of adaptation in future projections.

The effectiveness of specific adaptation measures, along with their potential for co-benefits or residual impacts, varies significantly depending on contextual, locational, and crop-specific factors. Furthermore, the combination of specific climate impact scenarios significantly influences the projected outcomes.

In practical terms, addressing escalating climate risks must be tailored to specific contexts and tailored enough to respond to evolving realities on the ground. Additionally, impact models commonly underestimate or inadequately represent climate extremes, limiting their ability to reflect adaptation needs under extreme conditions, which could strain systems to their limits. While known structural adaptation measures can mitigate some projected risks across sectors and regions, residual impacts persist across all warming levels, with effectiveness declining at higher temperatures. Adaptation tends to be more effective at 1.5°C warming, although residual damages are still projected at this level. Moreover, certain options have the potential to exacerbate negative effects (maladaptation) across sectors, regions, and warming levels, emphasising the necessity for context-specific approaches.

2.4.2. Socio-economic modelling

The interplay between physical and social systems is crucial in understanding the socio-economic impacts of climate change and societal transformation influence on the exposure to climate change-related impacts. However, these interactions are still not entirely understood, and this could lead to underestimated risks. Rising et al. (2022) showed that the economic evaluations are crucial inputs into policymaking and long-term planning processes. The quantification of climate risks reflects the probability distributions for possible impacts, but there are still great challenges related to the modelling uncertainties and economic valuation of climate change impacts and risks due to the complex economic implications (sectorial, multi-sectorial or cross-sectorial) and nonlinear social feedback.

The development of coherent frameworks for assessing the sectorial impacts of climate change are still limited. Several contributions applied detailed bottom-up empirical or biophysical modelling assessments s (Martinich and Crimmins, 2019; Ciscar et al., 2011), but there is still need for further efforts to translate biophysical risks into economic ones (Rising et al., 2022) and, even more, in social ones.

SE modelling is subject to complex uncertainties, which calls for interdisciplinary approaches to better understand and communicate modelling uncertainties and their impacts on decision-making (Espig et al., 2020), which is in support of the selection of appropriate adaptation policies. Furthermore, the uncertainties associated with the biophysical impact modelling on regions with prominent signals of a changing climate (hotspot areas), represent key knowledge gaps. This gap is critically important for the development of climate change adaptation strategies and policies, that should be supported by sound knowledge and understanding of the full range of biophysical impacts, which are characteristic to each geographical location.

The assessment of impacts and damages associated with the observed and expected climate change is a critical need for climate policy design and optimisation of risk management at both national and subnational levels. In this context, economic and social modelling has important contributions to the overall understanding of societal transformations and could provide valuable insights into the impacts of the ambitious climate policies towards achieving the goals of the EU climate change adaptation mission and EGD (Weitzel et al., 2023). Ciscar et al. (2019) emphasised the contributions of some large multi-model comparison projects such as: the Inter-Sectorial Impact Model Intercomparison Project (ISIMIP) project (Warszawski et al., 2014), which covers multiple climate impacts or sectors, and the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Rosenzweig et al., 2013), which focuses on a single sector, agriculture. Other recent contributions also addressed the impacts for specific sectors, such as on energy (van Vliet et al., 2016), transport (Bubeck et al., 2019), agriculture (Baker et al., 2018) and health (Mitchell et al., 2018), or for specific climate hazards, such as river floods (Dottori et al., 2018), coastal storms and sea level rise (Vousdoukas et al., 2018), and multi-hazard (Forzieri et al., 2018).

The socio-economic impacts of climate change are complex, with multi-sectorial and cross-sectorial facets observed throughout a wide range of geographical and temporal scales and susceptible to various climate and economic scenarios. Rising et al. (2022) showed that some knowledge gaps around the missing risks associated with climate change are related to the fact that such risks are not currently included in economic evaluations. These missing risks stem from: delays in sharing knowledge across disciplines; spatial and temporal variations of climate impacts; feedback and interactions between risks; deep uncertainty in knowledge; and unidentified risks. Rising et al. (2022) also emphasised the need to address these missing risks of climate change in economic assessments and decision-making processes, highlighting the challenges and the long-term goal of improving the representation and understanding of these risks.

Three flagship reports on food system transformation - the EAT Lancet Commission (Willett et al., 2019), the Food and Land Use Coalition (FOLU, 2019) and the special report from the Intergovernmental Panel on Climate Change and Land, with chapters devoted to food security and food system interactions (Shukla et al., 2019), highlighted some important socio-economic modelling challenges related to food security. These reports showed that SE modelling efforts still fail in incorporating efficiently the influence of producers in food chains, challenging the assessment of constraints and market failures faced by small producers in the context of climate change (OECD, 2021). Improved conceptualising and modelling food systems are needed, while promoting the inclusion of rural poor and overcoming unequal power relations-win to support the adaptation of food systems to the transformative natural and socio-economic contexts.

Socio-economic modelling of climate change

A core IPCC objective since its first assessment report of 1990 is to estimate the economic implications of climate change, and of mitigating it. There are three working groups in the IPCC AR6: WGII focuses on "Impacts, Adaptation and Vulnerability" and WGIII on Mitigation of Climate Change. However, a full benefit-cost analysis should extend beyond mitigation costs and include damage, adaptation, and potential co-benefits (driven by mitigation and adaptation actions).

IAMs link climate variables to economic outputs in the economic module to assess the effects of climate change policies on socioeconomic systems. IAMs can be divided into two categories: Process (P-IAMs) and Benefit-Cost (CB-IAMs), according to the content, the complexity and the level of detail in describing the climate-economic relationship (Weyant, 2017). CB-IAMs have been used since Nordhaus (1991) to examine trade-offs between mitigation and climate damage costs. A key assumption in IAM studies is the future social discount rate. Stern (2007) examined the cost of climate change for the UK Government, using a discount rate of 1.4% and found that early, deep mitigation actions were justified to avoid climate damages. Yet the future is normally discounted at higher rates in economic appraisals (Yohe & Tol, 2007). Computable General Equilibrium (CGE) models describe the relationships across multiple economic sectors and can evaluate climate impacts on production, consumption and trade for example. CGE models have the strength of being able to analyse direct and indirect economic effects of climate change across sectors (through price changes and substitution effects) while also considering adaptations (McDermott et al., 2021, Piontek et al., 2021). These CB-IAMs and CGEs have been the principal source of cost benefits and spill-over analysis of climate change for the last few decades. They usually use costs (mitigation, adaptation and damage) taken from other models such as econometric studies or P-IAM. For example, many studies are focusing on the cost of mitigating climate change only and its affordability. They have been summarised in a review paper by Köberle et al. (2021). These mitigating costs are often estimated by bottom-up technological energy system models (P-IAM) and specified in terms of a long-term change in gross domestic product (GDP) from a baseline without mitigation, however these studies only apply mitigation (emission abatement or removal). In parallel, econometric studies have attempted to estimate the actual cost of climate change using existing past physical and/or economic data. Some of these studies have then extrapolated forwards for future scenarios (Burke & Tanutama, 2019). Resulting actual damages have been found to be much higher than previously projected by P-IAMs and call into question previous assumptions. Finally, mitigation may also drive co-benefits such as better air quality, diets and overall health for example. These are difficult to assess because monetisation of the number of avoided bad-health or death through co-benefits is controversial and there is no agreement on a calculating approach (Robinson, 2007).

Cost-Benefit Integrated Assessment Models. CB-IAMs normally include several steps: (i) economic activities produce GHG emissions; (ii) higher concentrations cause global average temperatures to increase; (iii) higher temperatures result in economic losses in most world regions; and, (iv) climate policies are required to mitigate these losses (Nordhaus, 2019). CB-IAMs combine the mitigation costs, the sectorial impacts and the adaptation costs of climate change into a single economic indicator, such as GDP losses. As CB-IAMs can be used to determine the optimal climate policy and to calculate the abatement costs and the potential benefits of avoided climate change, they are widely used to determine the optimal emissions abatement path and to calculate the Social Cost of Carbon (SCC) (Weyant, 2014) and the climate-induced economic losses per unit of CO2 emissions (IPCC, 2022). In CB-IAMs the impacts, abatements and adaptation must be monetise with simplified forms of functions because there is limited or no physical representation of natural and human systems in the model except for simple economic growth or climate modules. However, they highlight key issues such as discount rates and damages, and can rapidly incorporate new understanding into cost and benefit projections. The principal BC-IAMs are the Dynamic Integrated Climate Economy (DICE) (Nordhaus, 2008), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2011), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff & Tol, 2013). Comparing the three models shows that despite major differences in damage components (Warren et al., 2021), the global annual losses in the three models do not vary widely. For a temperature increase of 1.5°C, the damage in DICE2016 and PAGE is about 0.5% of GDP, while in FUND it is about 0.7%. For an increase of 2°C, the damage in DICE and PAGE is about 1% of GDP, and in FUND about 1.1%. Damages arising from a 6 °C temperature increase are about 10% in PAGE, 8.5% in DICE2016 and 7.2% in

FUND (Tol, 2014). CGE models can represent different geographical scales (sub-national, national or larger geo-economic blocks) and analyse economic interlinkages between these regions (Vrontisi et al., 2022, Zhang et al 2021). Different models include different features modules such as land use, crops, forestry, energy, emissions and air pollution, to assess climate impacts. However, they can require very detailed data and computational power to solve optimisation problems when high sectorial, spatial and temporal dimensions are represented (Piontek et al., 2021, Zhao et al., 2021). Many CGE models have fixed damage functions translating the biophysical impacts of climate change into economic impact (Costantini et al., 2018), Unlike for CB-IAMs using aggregated damage function, CGE models can use a series of damage functions describing different climate impacts in different economic sectors (Piontek et al., 2021, Dellink et al., 2019, . Biophysical impacts are also directly influencing outputs (e.g. sea-level rise effects supply of land - Solomon et al., 2021, Knittel et al., 2020). A key issue when assessing economic damages with CGE models is the number of impacts included (Piontek et al., 2021) as overall costs are higher when a greater number of impacts are represented. Some studies only consider a single impact: agricultural productivity sea-level rise (Pycroft et al., 2016) or heat-related loss of labour productivity (Zhao et al., 2021). The results show some large regional disparities. Studies considering simultaneously several types of impacts includes: Takakura et al. (2019) agricultural productivity, undernourishment, heat-related excess mortality, cooling/heating energy demand, occupational-health cost, hydroelectric power generation capacity, thermal power generation capacity, and fluvial flooding and coastal inundation. The net economic loss is equivalent to 7% (4%–9%) of global GDP by 2100 under the RCP8.5 scenario and around 1% for RCP2.6. Wang et al. (2020) assessed crop yields, human health, labour productivity, sea-level rise, and residential energy demand and their results indicated global GDP total losses by 2050 of 0.7% for a NDC scenario, which reduced to 0.4% for a 2°C warming scenario. Dellink et al. (2019) projected global annual GDP losses of 1%–3% by 2060 when accounting for sea-level rise, agriculture, tourism, fisheries catch, hurricanes, disease and heat stress, and energy usage change due to cooling and heating. Kompas et al. (2018) accounted for agricultural productivity, sea-level rise and health effects on GDP, and estimate a global loss of 3% of world GDP in 2100 for a 3°C warming scenario and 7% for a 4°C scenario. The different sectors included and scenarios represented make overall results comparison harder to achieve than for CB-IAMs.

Process Integrated Assessment Models. P-IAMs seek to estimate climate change impacts at a detailed regional and sectorial level, with a focus on intra- and inter-sectorial interactions. They obtain not only estimates of the impacts of climate change on the economy, but also projections of the physical impacts of climate change (e.g., on reduced crop growth and land inundated by rising seas) to provide detailed policy options. In contrast, CB-IAMs have a more aggregated representation of climate change mitigation costs and aggregate impacts by sector and region into a single economic metric. Two representative P-IAMs are the IMAGE (Stehfest et al., 2014) and GCAM (Calvin et al., 2019). IMAGE3.0 contains a wide range of indicators on agricultural impacts, water stress, flood risk, land degradation and human development. GCAM, a model including multiple subsystems, such as macroeconomics, energy, land, water supply and climate. However, most damages are in this case expected to be given in physical units (e.g. biodiversity loss, yield changes or years of life lost) and not easily comparable overall damage for CB-IAMs but used mostly in CGE modelling.

Econometrics models. Three econometric methods have primarily been used to estimate the impact of climate change: cross-sectional approaches, panel data regressions, and long differences regressions. Each has strengths and weaknesses (Auffhammer, 2018, Dell et al., 2014). These models use data from various units of analysis observed in the same period to relate an outcome of interest (e.g., GDP, crop yields, industrial output) with economic actors (firms, consumers, countries, etc.) to climate data (usually temperature and precipitation). As for P-IAMs these methods can handle one specific sector (e.g. agriculture) or multi-sectors analysis (aggregated output). For temperature effect on national or regional GDP, Burke et al. (2015) find national GDP marginal loss (loss per 1°C increase) up to 1.2%. Burke & Tanutama (2019) observed at 11,000 districts level (but in 37 countries only) that marginal damage to regional GDP can reach 1.7%. Higher losses have been estimated by Kalkuhl & Wenz (2020), with marginal damage to regional GDP of 3.5%. When impacts of both temperature and precipitation are included, Waidelich et al. (2024) projections achieve reduction in GDP of 3% (10%) for a RCP1.9 (RCP8.5) and Kotz et al. (2024) conclude with higher losses of 20% (60%) for RCP2.6 (RCP8.5) by 2100. Gaps in SE modelling of climate change An important disagreement in the literature is the extent to which growth impacts could persist and further reduce long-term GDP levels. Globally by 2100 for an RCP8.5 when losses are not compounded, the models in Newell et al. (2021) project GDP losses of only 1%–3%, while Kalkuhl and Wenz (2020) find higher loss of 7%–14%. In contrast, while Burke et al. (2015) has lower marginal uncompounded GDP losses, the compounding of losses leads to

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a higher projection of a 23% reduction (Burke et al., 2018) for the RCP8.5 in 2100. Moreover, adaptation is an important factor affecting climate change estimates. Empirical studies do not directly incorporate adaptations into impact estimates, although those examining long time-series are likely to account for any adaptations that occurred. Where studies have identified adaptation strategies, the results are mixed. In a modelling study, it is more difficult to disentangle the impact of specific adaptation actions. On the other hand, the inclusion of structural, theoretical equations, especially in CGE models, may offer a more comprehensive framework able to include a wider set of adaptation strategies, including input changes (Schinko et al., 2020, Diaz and Moore, 2017). In summary, climate change is projected to reduce global GDP in all studies/models. Impacts on low-income countries are projected to be much higher than on high-income countries. Projections of the long-term impact of climate change on GDP vary widely, but impacts are higher for studies that consider several sectors with spillovers, include extreme weather and assume that GDP losses will compound over time. At sectorial level, not so much has been done for modelling social justice in relation to climate change. Looking at climate change mitigation, it can be noted that it is yet unclear to what extent modelling is supporting policy making towards a transition process entailing social justice. For instance, IAMs have become the dominant approach for envisioning different mitigation scenarios. While they are not intended to deal with justice, IAM assumptions and structure have justice implications that have not been explicitly discussed or clearly elucidated in critical accounts of modelling practices". Looking at energy transition, a review was done on 73 recent energy systems modelling studies, observing a diversity of approaches to account for energy justice. While models do show promise in being able to support a just transition, especially in terms of assessing distributional outcomes, many of the approaches in the literature are poorly connected to current energy justice goals and discourses, decreasing the studies' policy relevance and leaving policymakers with suboptimal planning support". However, something has been done not only in the above-mentioned studies. More broadly, we already noted that according to UNDP countries like Serbia, Costa Rica, and Zimbabwe are building a solid evidence-base for just transition by conducting qualitative and quantitative assessments looking at the socioeconomic impacts of a green transition. These assessments include economic modelling". Not so much has been done also for setting-up models related to climate change taking into account how climate change is affecting migration social justice. For instance, system models have been useful policymaking tools considering energy transitions that are low cost and low carbon, but it is yet unclear to what extent these models can also support a just transition and the combat of climate migration". However, this issue is considered in a few cases (such as McLeman, 2013) who have modelled migration as part of an outlook on how to improve the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis. In the Insurance sector, insurers are developing different tools based on risk assessment models to inform pricing insurance products, long-term strategic planning, product development, regulatory compliance and reporting and investment strategies. NatCatModelling Engine (NCME), developed by SwissRe, is one of the tools that allow to combine hazard models with vulnerability parameters and exposure modules to calculate the insurer's net loss resulting from a given ground up loss, supporting all possible insurance policy conditions. For the energy sector, it is worth mentioning the POLES2 (Prospective Outlook for the Long-term Energy System) model, which is a global simulation tool designed to develop energy scenarios up to 2050. It integrates technological trends, price elasticities, and activity variables to forecast final energy demand, accounting for inter-fuel substitution based on equipment flexibility. The model also calculates emissions for all Kyoto gases. This model was firstly used to analyse the impacts of climate change on the energy system within the EU FP7 project Climate Cost (Mima et al., 2011). Later, Pawl Dowling (2013) modified the model to isolate the impacts of climate change on energy demand, this analysis applies the climate effects from each scenario to the POLES energy demand model, which excludes climate impacts but includes other factors like GDP per capita, energy prices, and technological efficiency improvements. The European Optimal Electricity System Management Tool (Plan4EU) developed in the H2020 project Plan4Resis a modelling framework that allows to obtain a holistic assessment of the energy system, dividing the energy system in models that cover the different aspects of the energy system with a detailed description of the interconnections between these models (Olmos et al., 2023, Krey et al., 2019). It allows testing different demand and generation mix options, to estimate the global costs and inform the energy system planning: Assessment of the feasibility of different scenarios of generation mix and related to demand and behaviour; Evaluation of reinforcement needs (optimisation of generation/storage investments); Evaluation of different flexibility options (e.g., residential load management); and Assessment of specific risks of renewable energy plants by climate hazards, and adaptation options to cope with these hazards. Modelling the impact of climate change for the tourism sector considers a multi-regional modelling approach connecting the tourism markets and climate. Simulations based on Regional Distribution Models show that climate change will impact winter tourism in any scenario. Losses in the overnight stays for ski tourism in the Alps will occur if no adaptation strategies are considered, but also if shifts to more reliable areas, or shifts to both more reliable areas and other tourist activities beyond the traditional NUTS3 winter tourism regions are chosen (Prettenthaler et al., 2022). The prevailing tourism demand models use historical monthly data and regression techniques focusing on the influence on tourism of either (i) year-to-year climate variability or (ii) of intra-annual climatic variations on the seasonality (Köberl et al., 2016). However, the reliability of these models is limited by their dependence on specific emission scenarios, regional climate models and data quality. To enhance the precision of projections, it is essential to develop more comprehensive models that encompass a broader spectrum of scenarios and consider non-climatic factors, such as visitor behaviour and destination characteristics. This would necessitate the incorporation of economic and social variables, in addition to climatic variables, as proposed by Dube (2024) and Köberl et al. (2016). The effective modelling of rural tourism in the context of climate change also necessitates the creation of scenarios that consider the variability of local conditions, infrastructure and resource availability. The nonlinear dynamics of socio-ecological systems make forecasting the consequences of global changes, especially of current climate changes, on their evolution to be extremely difficult. The Methodological Assessment Report on Scenarios and Models of Biodiversity and Ecosystem Services (IPBES, 2016), presents a best-practice 'toolkit' for the use of scenarios and models in decision-making on biodiversity, human-nature relationships, and the quality of life. The evaluation of climate change impacts on food security is a complex task involving the analysis of multiple indicators across various dimensions, including food production, market dynamics, availability for the population, and external influences like import substitution. However, using integral or aggregated indicators for assessment is challenging due to the need to assign relative weights and interpret composite indicator values. Modern studies on food security often analyse different population categories based on social, demographic, territorial, or agricultural criteria. New methodologies involve cognitive economic and mathematical modelling, enabling the analysis of statistical indicators and the assessment of factors influencing food security changes. These methods can be used to predict future levels of food security (Prettenthaler et al. 2022).

2.4.3. Adaptation modelling

Terzi et al. (2019) notes the limited number of applications of some promising methods (e.g., system dynamic models, hybrid models) for multi-risk assessment in mountainous regions and the need for an integrated approach to address challenges related to the combination of information from the social and environmental fields and spatial and temporal dynamics. Inclusion of uncertainty factor in risk assessment in bioclimatic modelling is still an open issue (Rai and Singh, 2020). Among the approaches to climate risk reduction, collaborative analytical framework (Zhong et al., 2022) accounting for several sectors (e.g., energy, agriculture, biodiversity, socio-economic) impacted by a single factor (e.g. hydropower development) or Adaptive Resilience-Based management (ARBM) framework integrating eco-services and socio-economic systems (Anthony et al., 2015) are proposed. Rising et al. (2022) highlighted the challenge of incorporating the endogeneity of adaptation in climate change risk assessment frameworks. There is still a need for actionable knowledge to support strategies for reducing greenhouse emissions (decarbonisation) and developing adaptation pathways to the impacts of climate change.

2.5. Co-designing actionable knowldege

Co-design and co-production of actionable knowledge for climate change risk assessment involves collaborative processes between scientists, policymakers, further stakeholders, and community members. These approaches are centred on stakeholder engagement and ensure that the knowledge generated is relevant, credible, and usable for all parties involved André et al. (2023) highlighted the role of co-design and co-production of actionable knowledge in climate change risk and impact chain assessments. Synthesising the key insights and lessons learnt from six participatory initiatives from the Northern and Central Europe implemented in the framework of UNCHAIN project, it was shown that the stakeholder perspectives and needs may still remained hidden or partially untapped although the structured and stepwise approaches of risks and impact chains are highly effective methods for fostering the co-production of knowledge with key stakeholders and scientists. The key benefits of the stakeholder engagement and stakeholder-scientist interactions were the (i) improved understanding of climate risks, impacts and vulnerabilities of stakeholders; deepened knowledge of local and regional decision-making contexts and the need for tailor-made climate risk assessments of scientists; (iii) improved and long-termed scientist-stakeholder relationship in the process of knowledge co-design and co-production. Other benefits of stakeholder engagement for co-design and co-production in climate change risks assessments, derived from practice or lessons learnt, are:

- The enhanced relevance and accuracy of risk assessments, adaptation strategies and policy development – Vervoort et al. (2014) showed the benefits of farmer participation (related to the provision of local knowledge and context-specific information), in improving the relevance of risk assessments and climate change adaptation strategies in the agriculture sector and food security under climate change; however, Susskind et al. (2012) revealed some examples of lessons learnt on the use of a collaborative adaptive management approach in the management of natural resources as well as the prerequisites for avoiding the possible failures in stakeholder engagement experiments (i.e., establishment of clear goals and concrete objectives against which the progress can be measured, provision of tools and incentives to encourage participation and foster collaboration, establishment of clear roles and fact-findings protocols for promoting shared learning, delineation of well-defined processes and triggers for monitoring, assessment and adjustment of management strategies).
- Increased acceptance and legitimacy – van den Berg and Coenen (2012) showed how stakeholder engagement contributed to urban resilience in the framework of the Rotterdam Climate Proof programme.
- Capacity building and empowerment – Ebi and Semenza (2008) showed how community involvement improved the preparedness and resilience to heat waves. - Enhanced communication and awareness - a report of the International Renewable Energy Agency (IRENA, 2018) highlighted some of the co-benefits of stakeholder engagement in facilitating the transition to renewable energy and long-term reliability of the energy system. Involving stakeholders in the climate change risk assessment process is still challenging due to: (i) limited time and allocated resources for stakeholder engagement that could result in ineffective risk management; (ii) limited or lack of support from local stakeholders; (iii) complexity of local stakeholder needs for actionable knowledge; (iv) uncertainty in the risk assessment (Florin & et al, 2018 UNEP, 2020).

There are numerous contributions to the analysis of opinions and points of view of key parties involved in adaptation or responsible in adaptation planning, for measuring their level of influence and involvement in climate change adaptation (Fadeyi & Maresova, 2020, Osaka & Bellamy, 2020, Samaddar et al., 2019). A technical report of the UNFCCC (Conde et al., 2015) showed that participatory scenario building, simulation, role play, visioning and back-casting are techniques to be implemented with stakeholders to construct possible futures resulting from the combination of possible "coping ranges" and possible future "climate change".

Examining the stakeholder perceptions on climate change impacts and adaptation actions in Greece, Sebos et al. (2023) showed that understanding the perceptions and knowledge gaps of stakeholders involved in climate-affected functions is an essential step towards the implemention of effective adaptation policies and enhancing resilience. The promotion of opportunities for two-way communication between scientists and stakeholders is critically important, adding value and relevance to the tailored scientific information. Implementing targeted awareness campaigns for those responsible for adaptation measures is therefore vital. Addressing communication gaps and understanding stakeholders' perceptions are crucial for the success of climate change adaptation policies. This fosters a more comprehensive understanding of climate change implications and enhances the effectiveness of climate adaptation measures and risk management.

2.6. Existing platforms for decision support system

A Decision Support System (DSS) is a system which, by bringing data and relevant models together and performing analyses, outputs products such as indicators or reports to inform decision-making. Computer-based decision support platforms can provide users with a framework to explore options in a comprehensive way. This section provides some relevant examples of platforms or other tools that support the decision-making process for climate change adaptation planning and risk management.

CLIMADA - Economics of Climate Adaptation (https://wcr.ethz.ch/research/climada.html). CLIMADA is a probabilistic natural catastrophe damage model (https://github.com/CLIMADA-project/climada_python) that calculates averted damage (benefit) resulting from various adaptation measures, including grey and green infrastructure and behavioral changes. As an open-source model, it implements the Economics of Climate Adaptation methodology, facilitating climate-resilient development and climate adaptation and provides decision-makers a fact base to understand the impact of weather and climate on their economies, communities, and ecosystems. CLIMADA integrates hazard, vulnerability, and exposure data to generate risk assessments, with the flexibility to use any or none of the provided data. It features the LitPop exposure model for estimating economic and population exposure, and uses impact/vulnerability functions to combine these with hazards. CLIMADA provides global coverage of major climate-related extreme-weather hazards at high resolution via a data API, for several types of hazards such as (i) tropical storms wind and surge (Eberenz et al., 2021), (ii) river floods (Mühlhofer et al., 2024), (iii) agro drought (Waldschmidt et al., 2021), (iv) European winter storms (Röösli et al., 2021), (v) wildfires (Lüthi et al., 2021) and (vi) snow avalanches (Ortner et al., 2023). Other applications of CLIMADA are for the analysis of heat mortality impact on labor productivity (Stalhandske et al., 2022), assessment of uncertainity and sensitivity analysis for probabilistic weather and climate--risk modelling (Kropf et al., 2022) or evaluation of infrastructure failure cascades (Mühlhofer et al., 2023). The CLIMADA risk assessment framework is described in Figure 2.

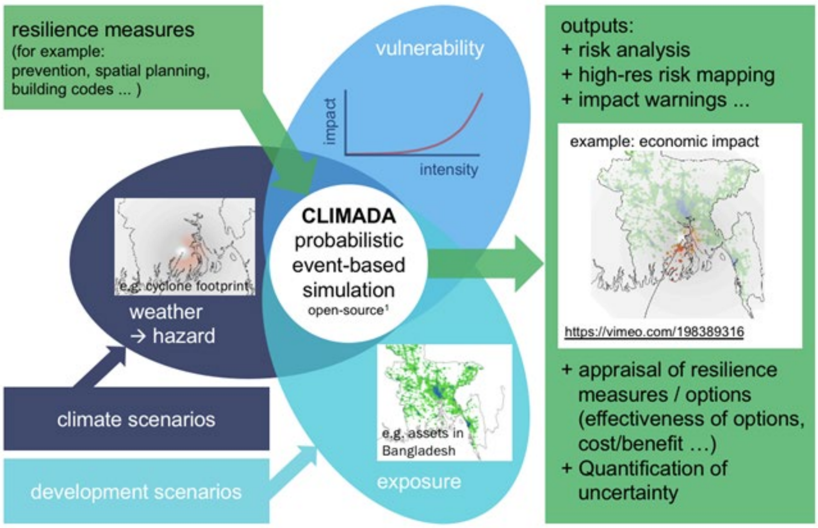


Figure 2. CLIMADA risk assessment framework

ADAPT2CLIMA Decision Support Tool (https://tool.adapt2clima.eu/en/home/). The ADAPT2CLIMA Decision Support tool aims to improve understanding of climate change and its impacts on agriculture, aiding farmers, policy makers, agronomists, and the agribusiness industry in adaptation planning (Fig. 3). Through interactive visualisations, maps, and graphs, the tool illustrates the effects of climate change on crop performance, water availability, and the agricultural sector as a whole. Additionally, it allows users to explore and evaluate adaptation options to enhance agricultural resilience.

The tool examines climate change scenarios for 2031-2060 under RCP4.5 and RCP8.5 for long-term planning and assesses extreme climatic scenarios (dry, wet, hot, cold) under RCP8.5 for short-term planning, helping farmers prepare for near-future climate extremes (Stranberg et al., 2014, Popke et al., 2013, Collins et al., 2011, Martin et al., 2010). Currently, the tool is implemented in Cyprus, Crete (Greece), and Sicily (Italy) but can be adapted for regional agricultural strategies in Italy, Greece, and Cyprus via the "apply the tool to your area" feature. Developed under the LIFE ADAPT2CLIMA project "Adaptation to Climate Change Impacts on the Mediterranean Islands' Agriculture," the tool is co-financed by the LIFE programme for the Environment and Climate Action (2014-2020).

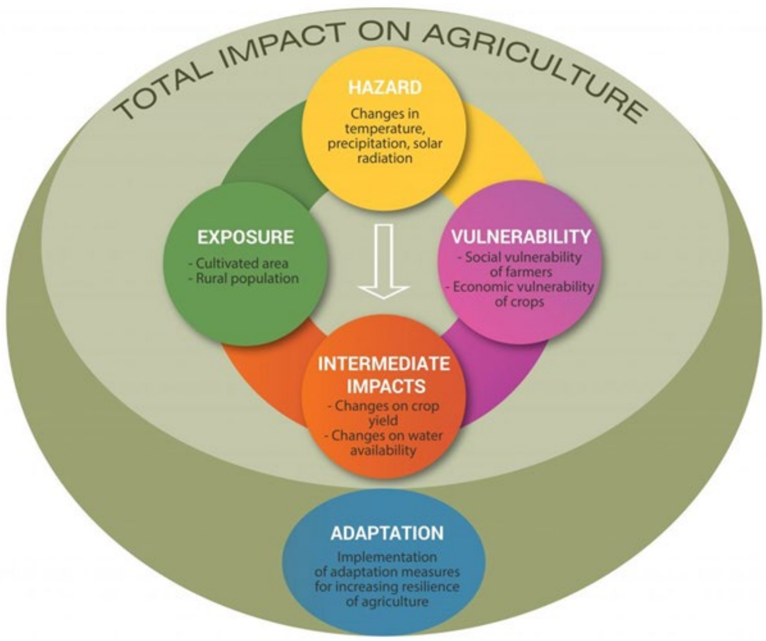


Figure 3. ADAPT2CLIMA - Impact assessment methodology

LandCaRe DSS – An interactive decision support system for climate change impact assessment and the analysis of potential agricultural land use adaptation strategies (https://www.landcare-ggmbh.de/). The main objective of LandCaRe DSS was to provide information on the complex long-term impacts of climate change and on potential management options for adaptation by answering "what-if" type questions (Wenkel et al., 2013). It is designed to aid decisions regarding the adaptation of agricultural land management to climate change at both farm and regional scales. The system considers the impacts of climate change on agriculture based on current and future climatic conditions, land use distribution and intensity, and soil properties. Conceptualised as a Spatial Decision Support System (SDSS), LandCaRe DSS is divided into three interconnected components: climate, ecology, and socio-economy (Fig. 4) The DSS combines scenario techniques with integrated spatial simulation modelling, promoting well-informed decision-making by farmers and stakeholders. It supports strategic decisions under uncertainty by allowing ensemble simulations to estimate the uncertainties in scenario outcomes and impact models. Additionally, LandCaRe DSS provides modules and tools for information and advice, as well as climate data analysis.

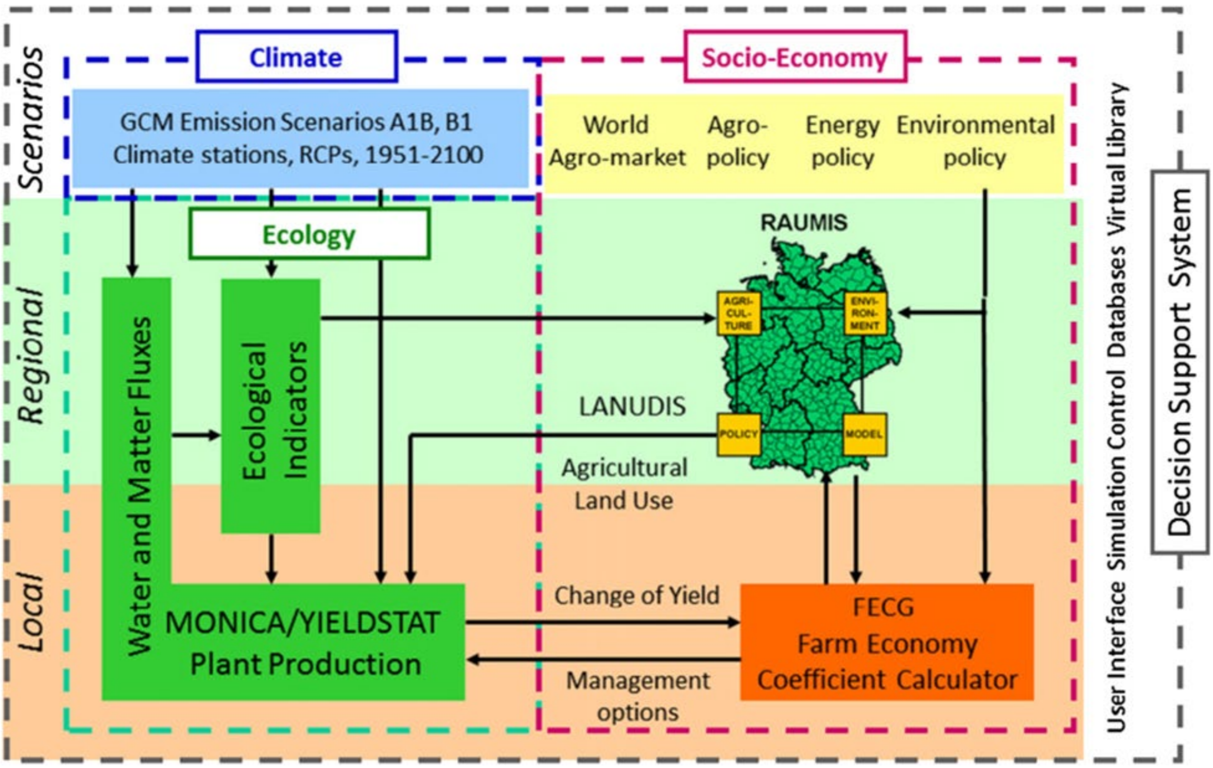


Figure 4. Conceptual framework of LandCaRe-DSS with different modules and levels of integration

3. Methodological Framework for a Harmonised Socio-Economic Risk and Impact Analysis

3.1. Guiding principles of the CROSSEU framework

CROSSEU aims to deliver a research-based framework for improving climate resilience and policy response to socio-economic risks of climate change and extreme events in Europe, by co-designing and co-developing a ready-to-use Decision Support System, and associated cross-sectoral actionable knowledge. CROSSEU relies extensively on the active engagement of stakeholders and policymakers to: (1) improve context-specific understanding of the socio-economic risks of climate change in different European regions, (2) co-develop decision support that integrates locally tailored tools, measures and policy options, and (3) bridge the gap between scientific evidence and practice mainstreaming results into mitigation and adaptation policies and measures.

The main pillars of the project are (1) modelling; (2) upscaling; (3) stakeholder engagement; (4) mainstreaming science knowledge into mitigation and adaptation policy options. To integrate all the pillars in a coherent framework CROSSEU defined the common language (CROSSEU Glossary) based mainly on the IPCC definitions and identified a set of operationalisation protocols based on the literature review (Section 2 – SoA), as well as on the results of the first exploratory workshops with sectoral stakeholders.

3.2. Modelling Protocol

3.2.1. Data collection and sources

CROSSEU identifies and collects climate and BGP data from existing repositories with observations, reanalyses and model results. This includes data on climate variables, climate-related hazards, and derived data on climate-related risks where appropriate. Where the BGP data represents a climate-related risk the data may refer to exposure to a hazard only or risk (resulting from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards). CROSSEU integrates available data (climate, BGP and SE), collected from different available sources (i.e., EU databases, national statistics, project results), with newly developed data (BGP and SE modelling outputs) at EU and case study levels. All the data will be collated in a comprehensive repository (the CROSSEU impact repository) that will feed the risk assessment framework, the CROSSEU DSS and ensure the background scientific information for upscalling. The CROSSEU impact data repository will be used internally within the project lifetime (described below).

The available data sources initially reviewed include:

- ERA5 - ECMWF/Copernicus
- E-OBS – ECA&D
- C3S - Climate Data Store
- ISIMIP
- IPCC Interactive Atlas (AR6)
- Climate Analytics Impact Explorer
- Tyndall Searchable global inventory
- Socioeconomic data at NUTS3 level based on Eurostat.
- EU funded projects – COACCH, IMPACT2C, PESETA and HELIX
- Euro-CORDEX regional climate model data

In the framework of WP1, an inital data scoping survey was conducted across partners from WP1 and WP2 (Month 5) to identify the specific BGP and SE data needs and formatting requirements for modelling activities within the consortium-The survey is being used to develop a consistent framework for extracting, processing and collating data within the impact data repository (Months 6-7) This follows the Tyndall Searchable Inventory Framework, and includes the following details:

- Data source;
- General category the climate or BGP indicator aligns to (e.g., climate variables, heat, drought,, agriculture, economic losses);
- Metric name (e.g., change in mean of daily temperature, annual expected damage from river floods);
- Units (e.g., percent change, losses US$);
- Spatial resolution of data set (original data resolution and post-processed data resolution included in the data inventory);
- Does the metric consider socioeconomic change and if so, which scenario is used;
- Full description of the metric;
- Metric categorisation (following IPCC definitions e.g., hazard, exposure to hazard, risk);
- Brief description of the model/method used to generate data;

- Limitations or key assumptions important for data interpretation (e.g., what is/is not included in the method used);
- If adaptation is/is not considered in the method;
- URL and related documentation.

3.2.2. Time-periods

For non-time dependent metrics that are not affected by CO2 concentrations or socio-economic data, data is extracted for global warming levels including 1.5, 2 and 4°C as far as available. Where data is not directly available at GWLs this can be inferred from available time-series data, selecting approximate 30-yr time slices centred on each warming level.

For BGP data that do include socio-economic data such as population, employment etc. data will be extracted for global warming levels at pre-defined timeframes: for example, 1.5°C in 2030, 2 and 4°C in 2050 and 4°C in 2100. Where data is available for given RCP/SSP scenarios this can be converted to GWLs. AR6 provides a complete updated set of warming points for both CMIP5 and CMIP6 models which will be used to convert time-series data into GWLs for given future time periods (Intergovernmental Panel On Climate Change (Ipcc), 2022), Table 4.5).

Whilst it is unlikely that a standard baseline can be derived across all data, as far as possible an observed reference/baseline period will be identified in the data and included in the data repository. Absolute change or percentage change in climate and BGP data can then be calculated from the baseline for each GWL and metric, allowing comparison across metrics.

3.2.3. Spatial outputs

Existing climate and BGP data are available at a range of spatial resolutions. The raw data are consistently aggregated to the country and NUTS1 and NUTS2 levels in line with T1.3. Downscaling to NUTS3 level will be carried out as required by WP2 to support risk assessments in each case study of the project.

Datasets may be provided using different coordinate/map projection systems. When collating the data the coordinate systems will be identified and transformations applied where necessary so different datasets can be easily and accurately joined or aggregated consistently across the project.

3.2.4. Modelling for CROSSEU Storyline (STL) case studies

The framework aims to facilitate comparability and consistency across case studies and other components of CROSSEU (e.g., expected fieldwork at the case-study levels in T4.2 and in T4.3).

CROSSEU will undertake modelling and qualitative analyses aimed at assessing the socio-economic risks of climate change and associated extremes within in WP1 and WP2. The CROSSEU assessment framework is structured around common analytical steps illustrated in the Figure 5, which could be used as an analytical structure both in WP1 and WP2.

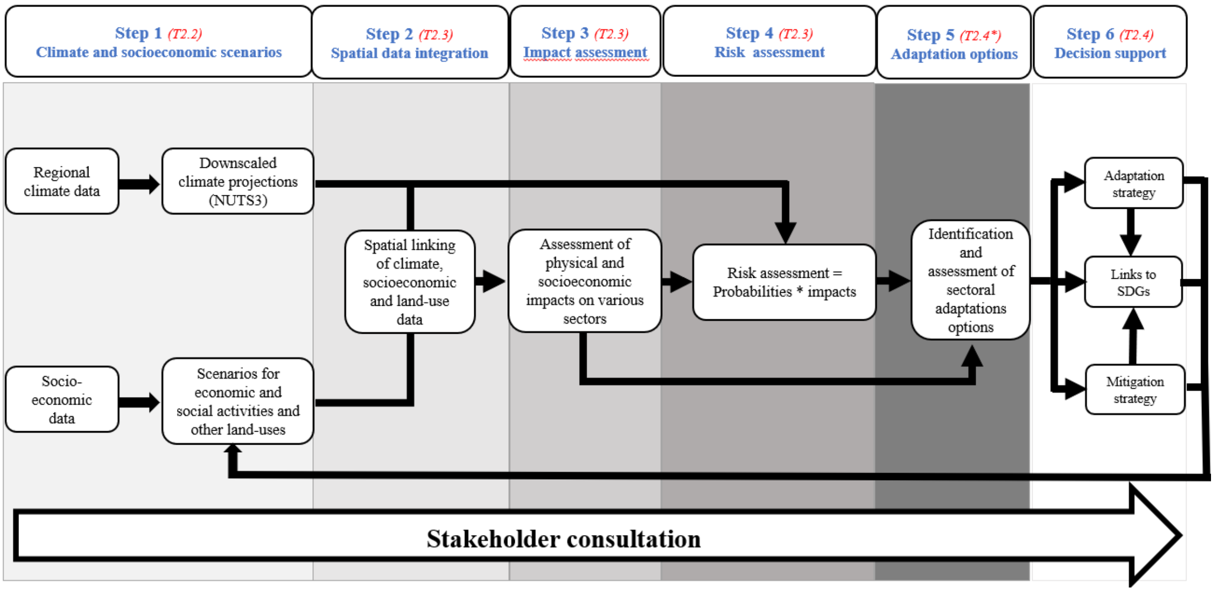


Figure 5. The conceptual framework for risk and impact assessment developed in WP2 (T2.1).

The CROSSEU assessment framework includes six steps:

- Climate and socioeconomic scenarios
- Spatial data integration
- Impact assessment
- Risk assessment
- Adaptation options
- Decision support

Step 1: Climate and socioeconomic scenarios. In this step, various socio-economic scenarios are created for each STL case study. Typically, there are two classes of scenarios: reference scenario (where current trends are projected into the future) and climate change scenario (where additional forcing from a changing climate is considered). In reference and climate scenarios at least two dimensions are considered: the physical climate projections and the socioeconomic projections. Physical parameters (e.g., temperature and precipitation) will be predicted using climate models or earth system models. Typically, output from coarse-resolution (global or regional) climate models must be statistically downscaled to a finer spatial resolution to provide more accurate data for local conditions. 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 SE scenarios describe future SE activities in the CCH. There may be several reference scenarios developed to conduct sensitivity analyses on different parameter values to determine which are the most important targets for further study to reduce uncertainty. The socioeconomic scenarios can include estimates for the uncertainty bounds for historic data and projected scenarios or have important assumptions noted in the projections. 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 for each of the STLs.

Step 2: Spatial data integration. In this step, a geographical representation of the socio-economic activities and land use is developed, which can be linked to the downscaled climate information inside the boarders of CCHs. To do this, it is necessary to clearly define the geographic boundaries of the case studies. For example, in a Danish context, relevant governance boundaries are municipalities, regions or national level. NUTS3 level data will be used in all case study areas. The spatial data integration can for example be modelled using GIS.

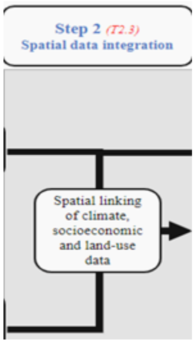
Step 3: Impact assessment. Downscaled data from regional climate models and global economic models, under different scenarios (RCPs, SSPs) will be used as input into impact models (e.g., flood models) to assess physical and socio-economic impacts of climate change on various sectors and geographical locations for each case study. The output of this process is a list of physical and socio-economic impacts, their severity, and the likelihood of occurrence. The measure of the impact will be expressed in monetary or non-monetary terms and both quantitative and qualitative measures will be applied. This opens possibilities for many different types of metrics and indicators to measure impacts. Therefore, a common guideline for assessing and reporting these impact metrics and indicators will be developed.

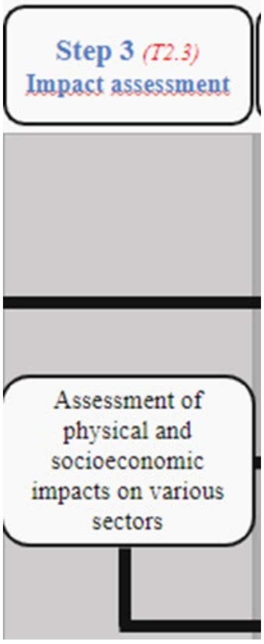
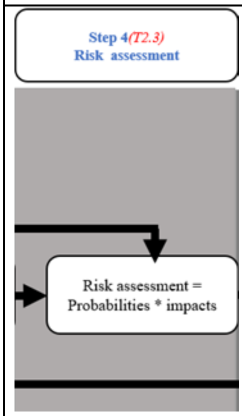
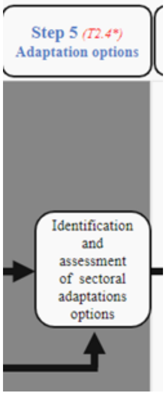
Step 4: Risk Assessment. Climate risk, defined as the probability of the occurrence of extreme events (hazards) multiplied by the impact of that event, is an important measure to support decisions on appropriate adaptation measures. The probability can be expressed in terms of either a return period or an annual probability. Many climate hazard events (e.g. extreme precipitation) will become increasingly likely. Therefore, probabilities of hazard events are time-dependent. The CROSSEU project considers four key types of climate hazards (heat, drought, storm, snow) that will be addressed in five out of the eight selected STL-based case studies(CS) in WP2, as follows: CSA#1 (heat), CSA#2 (drought), CSAs#3 and 4 (storm) and CSA#5 (snow).

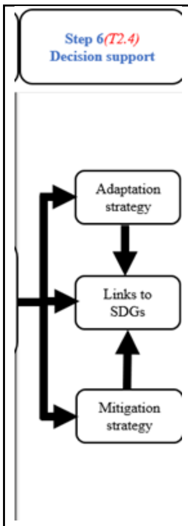
Step 5: Adaptation options. The next step is to identify the adaptation options based on the impact and risk assessment. The selection of adaptation options will reflect where there is a large potential gain in reducing the risk of climate events by adaptation. In addition to the direct benefits of adaptation due to risk reduction, the adaptation options can also have synergies and trade-offs with mitigation and other development-related goals in terms of SDGs or local development targets, which initially can be mapped for the adaptation options. Assumptions made in this stage will be used 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 T4.3 (dealing with the societal impact of adaptation policies related to social justice, including gender, and considering multiple forms of discrimination or inequality, social cohesion and social exclusion; the analysis will also help in documenting how policies can increase the capacity of different groups to adapt to climate risks).

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 the mitigation strategies and SDGs, will be included. In the further development of the common CROSSEU methodological framework integrating the outputs of the modelling effort for each case study (WP1 and WP2), we provide an example that shows the different steps that will be conducted in the selected case studies of the project. In the following case study table, we are showing the six steps planned for STL case study #3 Storm - Denmark/Germany.

Table 1. STL case study #3 Storm - Denmark/Germany (Preliminary attempt only for illustrative purposes)

	Approach Downscaled climate information is obtained from WP2. Socioeconomic projections for the case study area are based on local development plans for the cities involved including Aabenraa, Sønderborg, Flensburg, and Kiel Detailed land-use map based on digital platform, including houses, transport, industry etc	Analytical tool Data on plans and land use (digital database) https://kort.plandata.dk/spatialmap (only Denmark)
	Approach Spatial data integration in GIS (QGIS)	Analytical tool QGIS

	Approach Apply Damage cost model (OpenSource2-SkadesØkonomi) to quantify economic losses for various sectors and to identify other exposed assets. The assessment will be conducted using an overlay analysis of flood hazard maps with socioeconomic and infrastructure data	Analytical tool OpenSource2-SkadesØkonomi The model has a high geographical resolution of land use and estimates flood damage costs for several sectors. The stage depth damage functions in the model are based on statistics of past insurance payouts. Data and damage functions are only available for Denmark in the current version of the model. 
	Approach Combination of climate probability scenario from step 1 with step 3	Analytical tool GIS based expected annual damage (EAD) assessment and calculation of present-day economic value of future expected losses
	Approach Adaptation options are identified in a dialogue with stakeholders	Analytical tool Adaptation option cost model (to be developed)

	Approach The information from step 5 is combined with existing mitigation plans and available SDG strategies and priorities	Analytical tool The damage cost model (step 3) is to be extended with the other dimensions.

3.2.5. Treatment of uncertainty

When collating the climate and BGP data care will be taken to identify uncertainties as identified in the source documents/webpages/descriptions, for example, related to regional climate projections, sea level rise scenarios, or methods to quantify BGP risks. Information on uncertainties, as well as any limitations or key assumptions made in modelling the data will be documented for each metric. Data will be included for median/mean climate model ensembles and where possible at the 10th/90th or 5th/95th confidence intervals (dependent on what is available in existing online data sources). Estimates of the uncertainties in data arising from other factors including the difference between using outputs for the same metrics from different modelling groups, using one metric over another e.g., for heat stress, need to be considered by those using the data. Different concepts and representation of uncertainties will be applied to represent climate and BGP data and socioeconomic data.

Percentage changes in metrics are more robust to uncertainties of many kinds than are the absolute values, hence both will be included in the data inventory. The inventory will contain information about how the metrics differ when different patterns of regional climate change corresponding to different climate change models are used.

Climate or BGP metrics aggregated to the country/NUTS1/NUTS2 scale could mask more detailed regional variations within a country. This is particularly the case for large countries. On the other hand, projections for very small countries which may contain only a few grid cells, dependent on the data resolution, are less robust, but such uncertainties can be offset by having more detailed and accurate data available for small countries.

3.3. Upscaling Protocol

The upscaling process within the CROSSEU project aims to enhance resilience to climate changeand extreme events by integrating results derived from the selected case study areas centered on relevant event-based STLs and corresponding CCHs and replicating the successful adaptation and mitigation interventions in any other follower areas in Europe and UK subject to the same climate hazards (i.e., heat, drought, storm, snow), but showing different exposures to climate change . This process involves synthesising context-specific information and generating generalisable conclusions applicable across different regions, sectors, and stakeholder groups.

The further development of case studies including results, models, and methodology will include an ongoing evaluation of the methodological assessment framework to be applied in the CROSSEU case studies in relation to the state-of-the-art sectoral modelling of similar climate risks. More specifically, CROSSEU will built its approach on the results and key findings of other EU projects and research at the sectoral level for the selected CROSSEU STLs and case study areas. In a further step, the results retrieved from each case study will be used to develop critical assumptions, meaningfull in terms of upscalling in other follower areas subject to similar climate hazards (e.g., in terms of sensitivity analysis CSA results could be used to develop or improve more aggregate sectoral approaches). An example of this approach is that the case study on coastal floods will compare the case study will compare results with strong sectoral models within this area (e.g., the Diva model), and the work by Voudukas et al. (2018) as part of the EU project ACCREU. We have previously compared our detailed analysis of Danish cases with such studies, and it is obvious, that the studies done by aggregate sectoral models provide very different results than what we get in detailed case studies. There are various reasons, including aggregation levels for land use data, damage cost functions that do not reflect experienced damages and data on storm surge levels. It would then be interesting to see if choices of parameters on such aspects are to be integrated into some of the more aggregated sectoral models as an upscaling exercise. Similar approaches will be developed for other case studies.

3.3.1. Data requirements

To maintain the consistency between case studies and the upscaled outputs to the DSS, it is essential to ensure the availability of datasets with a comparable spatial and temporal resolution across the whole EU in each STL case study, in line with the upscalling objectives and follower areas specificity 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. Alternatively, data availability in the partners' countries via case study leaders will be investigated.

3.3.2. Modelling data

The outputs from detailed case studies will be integrated into a broader assessement framework of socio-economic risks and vulnerabilities associated to climate change. To achieve a comprehensive understanding, data from sectoral case studies will be utilised to cover larger regions including the areas subject to the selected 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.

The applicability of the sectoral models used in the case study STLs on the European level will be examined to identify their limitations and benefits for further exploitations in support of upscalling. Sensitivity analysis will be employed to explore how different parameters affect outcomes, to refine sectoral risk models. Adjustments are expected to be needed in relation to the selection of relevant parameters, aggregation levels for land use data, damage cost functions to improve the accuracy and reliability of risk models.

3.3.3. Upscaling procedure

The upscaling procedure consists in three main steps:

- STLs Development: Climate hazard scenarios will be developed based on European sectoral studies, producing a range of possible perspectives on the local or regional exposures under different climate change and socio-economic contexts. In this step, the upscaling procedure will involve consultations with sectoral stakeholders (CSA level) to ensure that these scenarios are relevant for the local scale and target sectors, meet the local expectations and needs for decision-making and consider the variety of the regional contexts.

- Stakeholder Engagement: Workshops and consultations will be organised to present preliminary findings to stakeholders from diverse sectors and regions. Feedback from these engagements will be integral in validating the provisioned scenarios and refining the further steps towards upscalling in follower areas
- Comparative Analysis: Through comparative analysis, commonalities and differences between various event-based STLs will be identified. This will allow for the development of comprehensive cross-sectoral conclusions. Synthesising these approaches and leveraging comparative analysis will build mutual understanding across different regions and between private and public actors to facilitate the upscalling of results and validated adaptation options in follower areas

3.3.4. Integration of quantitative and qualitative data

Both quantitative and qualitative data will be scoped and 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 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.

3.3.5. Barriers and uncertainties

It is crucial to identify robust findings and gaps in the data and analysis to address any uncertainties and limitations. This includes examining discrepancies between detailed case studies and aggregate sectoral models to understand and mitigate differences.

Strategies will be developed to address identified barriers and uncertainties, ensuring that outcomes remain robust and reliable.

Promoting cross-sectoral and regional collaboration will be key to maximising the impact of M&A strategies.

3.4. Protocol for co-designing the DSS

Co-design is the process of joint development, actively involving stakeholders, and the first action in operationalising the CROSSEU Decision-Support System (DSS). This process is intended to strongly involve a primary core of users and stakeholders from all case studies. This protocol ensures that the CROSSEU DSS is user-centric and aligned with its potential users' specific requirements and workflows.

3.4.1. Co-Designing Aims and Approach

CROSSEU aims to undertake co-design and co-production processes throughout the project duration to develop an integrated and ready-to-use tool, in support of climate change adaptation. Co-design reflects a different approach in the traditional researcher-stakeholder relationship. The co-design approach enables a wide range of people to make a creative contribution in the formulation and solution of a problem (Slinger et al., 2023). The project also aims to work directly with the most relevant stakeholders and policy makers in the case study areas from (but not limited to) following sectors: energy, industry, agriculture, biodiversity conservation, transport, civil-society, academia.

3.4.2. Stakeholder engagement for co-designing the DSS

The co-design approach goes beyond simple consultation by making effective collaboration between researchers and stakeholders affected by different challenges under climate change. In this context, stakeholders who are using their own experience become central to the design process. Key stakeholders will contribute to defining, developing, implementing and reviewing the solutions to effective climate adaptation.

During the first three months of the project, an initial stakeholder mapping has been carried out. The DSS developed by the CROSSEU project is based on the selected CS and regions. The preliminary list of stakeholders is not intended to be exhaustive and will be further updated during the next phases of the project. Considering stakeholder relevance and resources, stakeholder participation levels are defined as follows: information, consultation, advice, and co-production.

3.4.3. Co-designing activities

Co-design starts from an initial knowledge base to inform the stakeholders, enabling them to add their perspectives and experiences. The knowledge base will help in understanding the broader landscape in which the project is situated, identifying resources and limitations, reviewing the best practices from what has succeeded elsewhere to apply them mutatis mutandis.

Co-designing activities will be carried out from the beginning of the project to identify and gather at the same table the relevant stakeholders. This process aims to obtain local knowledge and expertise regarding how climate change mitigation and adaptation, may influence ecosystem functioning and stakeholders' activities.

A stepwise approach is used for co-designing activities in each pilot area, as follows:

- Stakeholders identify the specific pressures for their pilot area (by selecting from a defined list);
- Ecosystem Services (ES) are identified by the stakeholders in each pilot area using a harmonised list of ES;
- A collective socio-ecological system analysis is carried out using Fuzzy Cognitive Mapping (FCM);
- Stakeholders identify possible responses (e.g. management options and restoration measures).

Co-designing activities include:

- Connecting (network building, connecting stakeholders, organising meetings, leveraging other networks, transdisciplinary)
- Translating (communicating, knowledge brokerage, translating between disciplines and across the science-policy boundary)
- Organising learning (capacity building, organising knowledge exchange, summer schools).
- Collaborative design (generating ideas, iterative prototyping)

3.4.4. Co-development and operationalisation of the DSS

Decision support systems (DSS) help deal with climate change mitigation and adaptation problems and by helping users explore different possible scenarios by combining knowledge, data, and models in a flexible and easy-to-use manner (Engelen et al., 1997). The DSS will support different decision-making processes and adapt over time to the needs of the user through interactive and iterative processes (Rutledge et al. 2007). An effective design, development, delivery, and use of a DSS requires considering transdisciplinary interactions among different scientific organisations and stakeholders from various backgrounds and expertise. The main focus should be on technical considerations, including determining the scope, the level of detail for the DSS and its components, appropriate technologies, and the intended users and their usage methods.

Co-development Activities to be explored with different stakeholders:

- Needs Assessment:
- Conduct a needs assessment to understand the specific requirements of different stakeholders regarding decision support for sustainable management and climate change adaptation.
- Identify the types of information, data, and tools needed to support decision-making processes.
- Data Collection and Analysis:
- Collaborate with scientists, researchers, and environmental organisations to gather relevant data on case study areas
- Analyse data to identify trends, patterns, and vulnerabilities associated with climate change impacts.
- Scenario Development:
- Work with stakeholders to develop plausible climate change scenarios that represent different future conditions and potential impacts in the case study.
- Use scenario planning techniques to explore a range of adaptation options and management strategies.
- Model Development and Testing:
- Test and validate the models with stakeholders to ensure accuracy and reliability.
- Decision Support Tool Design:
- Design user-friendly decision support tools that allow stakeholders to explore different adaptation scenarios, assess risks, and evaluate the effectiveness of various management options.
- Incorporate interactive features, visualisations, and mapping capabilities to enhance usability and accessibility.

- Capacity Building:
- Provide training and capacity-building workshops to empower stakeholders with the knowledge and skills to use the decision support system effectively.
- Foster collaboration and knowledge sharing among stakeholders to promote collective learning and adaptive management approaches.
- Policy Integration:
- Engage policymakers and decision-makers at various levels to ensure that the findings and recommendations generated by the DSS are integrated into policy development processes related climate change adaptation and mitigation.
- By engaging stakeholders throughout the development and implementation process, the decision support system can become a valuable tool for promoting sustainable management practices and enhancing resilience to climate change.
- Evidence-based decision-making can be informed by indicator trends, early warning tools and platforms, and citizen science for a better understanding of local infectious disease risks and a mapping of vulnerable populations. The proposed approach can also provide an understanding of the impacts and cost-benefits across various mitigation and adaptation efforts.

3.4.5. Evaluation, feedback collection and review of the DSS

Evaluation, regular feedback collection and review for the DSS will be conducted during individual workshops for each CS.

The stakeholder engagement will be done at scheduled time frames also using a stepwise approach:

- Deliverable dissemination
- Interviews, and questionnaires sent before the workshop
- Focus groups and exercises during the workshop
- Evaluation forms

This process will serve for continuously updating and enhancing the decision support system based on new data, emerging research, and evolving stakeholder needs.

3.4.6. Treatment of uncertainty

Stakeholders are involved from the early stages of the project, and their active and effective involvement is highly necessary for an efficient development of the project tools.

In the co-design process, the uncertainties will be addressed using a two-way approach (Pulido-Velazquez et al., 2023):

- Top-down approach in relation to uncertainty in the scientific knowledge (e.g., associated with the models limitations, climate projections, local scenarios etc.). This will be applied in the modelling activities, as described in the modelling protocol, and various strategies will be employed to communicate it efficiently to stakeholders, aiming to improve the usability of the developed knowledge for the decision-making process.
- Bottom-up approach in relation to uncertainty arising from the stakeholder's involvement (e.g., different perspectives, priorities and needs). This will be implemented through the co-design and co-production activities (e.g., collaborative design, scenario development), aiming to 'generate validated results that are meaningful for local stakeholders, decision-makers and information users' and to design climate adaption options 'integrating the goals of economic development, social acceptability and environmental sustainability'.

3.5. Protocol for integrating CROSSEU results into mainstreaming the science knowledge in M&A policy options

3.5.1. Identification of key scientific findings

CROSSEU conducts an analysis of the M&A policies and measures in EU and at the national level (considering national policy frameworks) (T4.1), analyses climate change impacts and sectoral policy responses relevant for the STLs and CCHs (T4.2), analyses social aspects and consequences of M&A measures in relevant policies (T4.3), analyses climate change-related economic and finance policies (T4.4), and derives knowledge-based recommendations for ambitious climate policy response in support of M&A (T4.5). Analysis at the national level will be limited to the European countries represented in CROSSSEU (Austria, Check Republic, Denmark, France, Germany, Italy, Romania, UK).

The successful completion of these activities strongly depends on the integration of results from other CROSSEU tasks and activities.

To collect relevant information an "Event-based storyline information template" is being collaborative developd for each of the eight storylines. This template includes sets of open-ended questions focusing on:

- Response and adaptation policies.
- Existing instruments and policies.
- Policy responses to cope with climate change.

These sets of questions were developed for use of partners conducting stakeholder consultation activities in the CSAs. Information from transcribed interviews will be included in the analysis (T4.2, T4.3, T4.4), which will then feed into the development of policy recommendations (T4.5).

3.5.2. Analyses of current M&A policies

The activity of anlysis mitigation and adaptation measures in relevant policies (T4.1) is focusing on:

- Entailing a systematic and comprehensive analysis of the policy and institutional framework, and instruments of Mitigation & Adaptation at EU and national levels.
- Capturing the stated goals, time frames, cross-sectoral and-scale interlinkages, and synergies and possible contradictions between sectoral driven policies.
- Identifying synergies between Mitigation & Adaptation measures, and identify bottlenecks and barriers in decision, implementation and monitoring process.
- Assessing the scope of the various policy fields for societal transformation with specific focus on their role for climate change adaptation, environmental conservation and sustainability.

The framework aims to help to facilitate comparability and consistency across the EU countries in the identification and analysis of current M&A policies and measures at the EU level and at the national level in the European countries represented in CROSSEU (Austria, Check Republic, Denmark, France, Germany, Italy, Romania, UK). Relevant international policies and frameworks will be also considered.

Only on-going policies and measures (that is, the policies and measures that are being implemented or that should be implemented based on the regulations in force) will be considered.

Two main tools, one for the identification and one for the analysis of the policies/measures are being prepared:

- A guide for the identification of the relevant policies (fiscal policies, incentives/subsidies, regulatory policies, information/awareness, support, etc.) and measures functional to mitigation, such as those for improving energy efficiency and opting for renewable energy, increasing the numbers of journeys in towns by bicycle, reducing the number of flights and taking more trips by train or in shared cars, enhancing industry, agriculture, fishing and livestock farming towards ecological standards; and functional to adaptation, such as those for increasing communities resilience, erecting buildings and infrastructure that is safer, replanting forests and restoring damaged ecosystems.
- A grid (or protocol) for analysing the policies and measures identified - this will include items such as stated goals, real goals, time frames, means of implementation, achieved results, expected results/impacts, actual results/impacts, actors involved, cross-sectoral and scale interlinkages, bottlenecks and barriers in the implementation, costs. Of course, not all these items can be documented for each policy/measure identified. A core issue should be to investigate on synergies/co-benefits and trade-offs/contradictions between adaptation and mitigation policies/measures.

The use of these tools will allow the standardisation of the analysis of the relevant policies and measures.

Alongside the actual analysis of policy documents, interviews with experts will be conducted at case study level, at national and European level:

- 2-3 interviews per each of the 8 case-studies among their main stakeholders;
- 4-5 interviews per country involved (to be selected among the policymakers who have had the greatest influence in the set-up of the policies/measures analysed and/or in their implementation (for example among those who are responsible for the EGD at the national level);
- 4-5 interviews at the European level (same criteria as above);

It should be considered that documents describing the relevant policies and measures will be mostly available only in national languages. In this case the analysis will be carried by the responsible partner with competencies in the language in question.

3.5.3. Translation of scientific knowledge

Translating results from impact modelling of sectoral socioeconomic risks of climate change into actionable policy recommendations for ambitious climate mitigation and adaptation is a critical process, bridging the gaps between research findings and the decision-making process. It entails transforming complex scientific evidence, and theories into applicable strategies that address societal challenges, reduce the socioeconomic risks of climate change and promote sustainable development.

Firstly, it is crucial to comprehensively analyse the modelled impacts across the twelve CROSSEU sectors to understand the interconnected vulnerabilities and opportunities. Next, stakeholders from government, academia, NGOs, and communities should be engaged to ensure diverse perspectives and expertise are considered (and their different positions should be compared adopting a “transdisciplinary" approach and, if needed, also negotiations). From there, findings must be synthesised into actionable, knowledge-based options and recommendations. Finally, recommendations should be tailored to specific policy contexts, considering political feasibility, institutional capacity, and socio-economic considerations.

3.5.4. Capacity building

The policy recommendation activity will combine findings from all the previous analysis carried out (T4.1, T4.2, T4.3, T4.4), as well as the stakeholder engagement (WP5), modelling results (WP1 & WP2), and the DSS outcome (WP3) to develop recommendations for ambitious and effective climate policy responses and thus increase stakeholder knowledge and understanding to identify, and capacity to implement, policy responses to climate change.

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3.5.5. Treatment of uncertainty

Uncertainties that could occur are complex and relate to the diverse nature of the analyses performed.

The availability and quality of data on existing M&A policies and measures can vary significantly from country to country and incomplete or inconsistent data prevents comprehensive analysis. In addition, the quality and representativeness of the information gathered from stakeholder consultations and interviews may vary, which has an impact on the robustness of the analysis. In addition, the level of stakeholder involvement and cooperation could vary, affecting the depth and breadth of information collected. Tailoring policy recommendations to specific national contexts involves uncertainties in understanding and incorporating local insights, further complicating the process. Addressing these challenges is essential to ensure the effectiveness and relevance of analysis and recommendations.

To address these uncertainties, links will be established with local stakeholders and organisations to improve access to comprehensive and high-quality data. To manage policy variability and diversity, a flexible analytical framework will be adopted to adapt to different national policies and contexts, and the involvement of local decision-makers will also help to understand the nuances of local policy implementation.

4. Stakeholder engagement framework

4.1. Introduction

Stakeholder engagement is the foundation for developing and testing a "decision support system" to ensure improved resilience to climate change and associated socio-economic risks in Europe. Co-design workshops for interacting with project partners and sectoral stakeholders are used in the early phase of the CROSSEU project as an effective way of stakeholder engagement. These workshops will lead to a continuous exchange of knowledge and ideas with members of the scientific community, policy makers and practitioners for providing robust, trustworthy and actionable science-based information through the CROSSEU DSS.

4.2. Objectives

The CROSSEU project aims to provide a research-based framework for enhancing climate resilience and policy response to socio-economic risks of climate change and extreme events in Europe. To achieve this, an active participation of various sectoral stakeholder groups is required for (i) improving the context-specific understanding of the nature and extent of the socio-economic risks driven by climate change in various timeframes (e.g., 2030, 2050, and 2100), scenarios, and regions; and (ii) co-developing a decision-making support that integrates tools, measures, and policy options to address the socio-economic risks and climate-related needs, in a cross-sectoral and -regional perspective.

The key objectives of the stakeholder engagement are:

- Identification and selection of the relevant public, private and civil society stakeholders for co-knowledge production to secure the relevance of the CCHs for different sectors and European areas. The focus is on health, social justice, migration, finance, insurance, energy, tourism, transport, biodiversity and ecosystem services, forestry, agriculture and food security, and water management, which are analysed for four CC sensitive systems (urban, rural, coast, and mountain area) across countries and European regions (i.e. Central and Eastern, Northern, Southern, and Western Europe);
- Collection of user requirements via workshops with stakeholders. Understanding the requirements of the stakeholder users is essential

to maximise the impact of the information provided by the CROSSEU DSS and to deliver a notable User Experience.

- Active collaboration and consultation with stakeholders are key aspects in CROSSEU in the co-creation of a science-based and demand-driven DSS, in the upscaling results of STL case studies as a core mechanism to increase the relevance and awareness of science-based knowledge, and for testing and validation of DSS functionalities with target users allowing the exploration of results and retrieving feedback.

4.3. Target participants

Public, private and civil society stakeholders from Europe acting in the following sectors (Fig. 6) in relation to the four climate hazard STLs selected in CROSSEU are listed below:

STL Heat:

- Health sector

STL Drought:

- Agriculture sector and Food security;
- Energy;

STL Storm:

- Water Management sector;

STL Snow:

- Civil protection;
- Tourism sector;
- Forestry;
- Transport.

STL Cross-sectoral multi-hazard risks:

- Biodiversity.

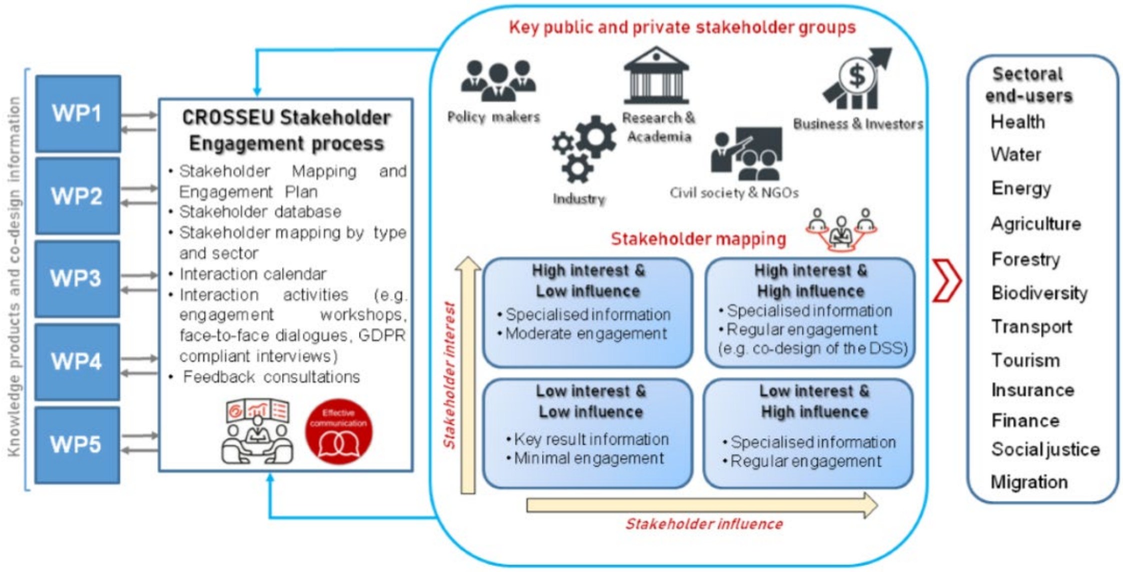

Figure 6. CROSSEU stakeholder engagement framework

4.4. Activities and results

The effective stakeholder engagement was carried out during T1.1 by organising four national workshops in Italy, Romania, Czech Republic and Denmark and one workshop at European level (Fig. 7).

Figure 7. The 1st CROSSEU stakeholder engagement workshops.

The aim of the workshops was to introduce the sectoral stakeholders to the issues addressed by the CROSSEU project and to set-up the framework for their involvement through a continuous exchange of knowledge and ideas with members of the scientific community, policy makers and practitioners to develop and test a "decision support system" to ensure improved resilience to climate change and associated socio-economic risks in Europe.

Active discussions during workshops have been guided by the following questions which the organisers asked the stakeholders:

1. What are the main impacts of climate change in your sector?
2. What specific information or data do you feel is lacking when you address the climate change-related risks in your sector?
3. Do you already use a Decision Support System?
4. Are you available to test the DSS during the project?
5. In which of the six steps of the case study would you prefer to be involved?
6. Do you have any data/information you can share that would be beneficial for the case study activities?
7. What is the level of engagement would you agree to be considered within the CROSSEU project?

4.4.1. The 1st CROSSEU stakeholder engagement co-design workshop in CSA #4 Storm – Italy

About the event

The workshop was held online on 27th March 2024. Eight stakeholders - from different organisations belonging to different sectors - participated. Participants were informed that project's stakeholders will be engaged in the co-creation of the platform, which will be informed by their demands and needs. Specific attention was devoted to the detailed explanation of CSA#4, including an explanation of the foreseen involvement of the stakeholders in its activities. The remainder of the workshop was dedicated to an active discussion, which was guided by a series of questions that were asked to the stakeholders.

Participants from Italy

The workshop organised in Italy targeted the relevant stakeholders from the sectors affected by floods and flash floods. Participants belong the following sectors: water management (43%), agriculture and food security (15%), environmental conservation and management (14%), tourism (14%) and transport (14%) (Fig. 8).

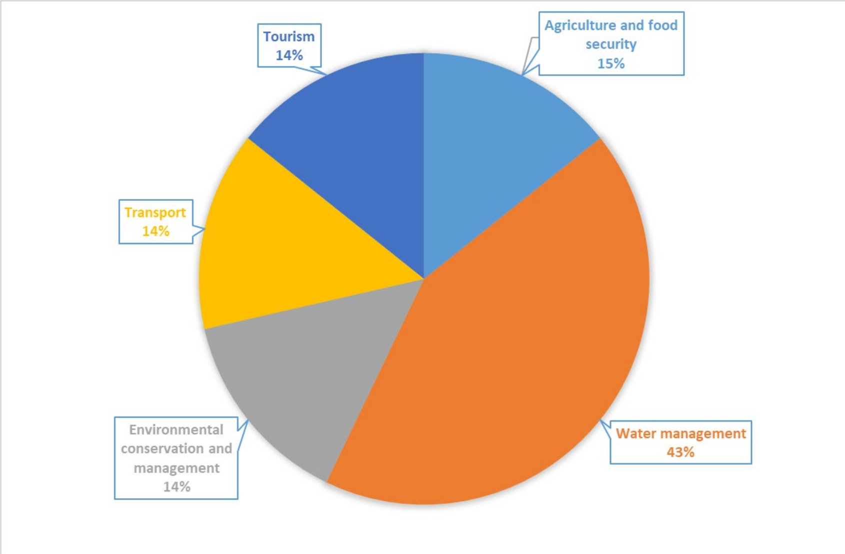

Figure 8. Organisation's activity sector of the relevant stakeholders for CSA#4 in Italy

Stakeholder’s feedback

Water management sector. Stakeholders representing water management sector are aware about the increase in frequency of hydro-geological risk and they expressed the need for a modern and flexible approach to hydro-geological risk, considering unpredictable factors and territorial conflicts. One of them has been involved in the development of a decision support system to define priorities for action and responsibilities in public spending and mentioned that his organisation is willing to share data, experience, and knowledge and offered support for applications of their decision-making system, especially for operational comparisons.

Another stakeholder was interested in the topic of climate change because it has significant impacts on regulations concerning the design of hydraulic works and spatial planning, especially from an urban planning perspective. He stated that while there is no specific legislation governing the assessment of climate change in these areas, the effects are tangible, and he wished to understand how to be proactive in addressing them. He mentioned that he has data on past events and existing protective works that he could make available for the project.

Another feedback has been received from the part of one stakeholder involved in water services and infrastructure sector that is affected by climate change. He focused on two main aspects: i) water availability and quality and ii) drinking water quality and purification. Regarding the former, he highlighted the impact of droughts on water resources. His organisation recently carried out a modelling work to predict water availability until 2050 in mountainous areas of Northeastern Italy. Regarding the latter, he noted that climate change affects the increase in microbiological risk. Furthermore, extreme events such as floods and flash floods recently compromised several purification plants in the mountain area of Northeastern Italy. He also highlighted how floods and flash floods can disrupt the provisioning of tap water in residential and industrial buildings. Finally, he stated his availability to contribute to the co-generation of impact scenarios and to host pilot actions that may be carried out within CSA#4 activities.

Representant of ARPA Veneto offered to provide specific data that may be needed for CSA#4 activities from the various departments of ARPAV.

Tourism. The significant impact of climate change is recognised also in tourism and biodiversity sectors.

One of the stakeholders discussed the importance for the Veneto Region to consider climate change in the tourism context. He reported the following main impacts of climate change on the tourism sector: i) coastal erosion; ii) disruptions in the transport network; iii) shortened winter seasons and reduction of snow levels. He emphasised that the latter is a paramount socio-economic issue in the Veneto region, as the tourism sector of its mountain area heavily relies on snow related winter activities. He proposed the implementation of an advanced decision support system, based on data analysis and scenario forecasting, to understand the consequences of mitigation actions or lack of actions. Marchioro underlined the importance of including tourism stakeholders in decision-making processes, given their expertise in the field of the destination governance. He reported that the Veneto region is available to share data on tourism, that can be used within CSA#4 activities, including destination sites and tourist's satisfaction. Finally, he stated his availability to test the project DSS.

Another stakeholder representing tourism sector emphasised the damage to tourism infrastructure caused by climatic events such as the Vaia storm, which led to the loss of a visitor centre and damaged trails and picnic areas. He is particularly interested in including river renaturation interventions among the possible adaptation/mitigation options to deal with the impacts of climate change. He also stated his interest in the DSS developed within CROSSEU.

4.4.2. The 1st CROSSEU stakeholder engagement co-design workshop in CSA#2 Drought, #5 Snow and #6 Cross-sectoral multi-hazard risk – Romania

About the event

The event was organised in Romania on March 28, 2024, by MeteoRo in collaboration with University of Bucharest. During this meeting, the stakeholders have been introduced to the general context of the CROSSEU project and to the selected case studies from Romania. In addition, a series of practical demonstrations on accessing the RO-ADAPT Platform, that provide current and future climate data for different sectors of activity, have been presented.

Participants from Romania

The workshop organised in Romania targeted stakeholders (50 participants, from 17 institutions) from different sectors (Fig. 9) and with different profiles: governmental (Ministry of Agriculture and Development Rural, Ministry of European Funds, Romanian Waters National Administration, National Road Infrastructure Administration Company, etc.), academic (Polytechnic University of Bucharest), research (Danube Delta National Research and Development Institute S.C.D.A Pitești, etc.), NGOs (WWF Romania), private companies (TQM SRL), county administrations (Salvamont-Salvaspeo Brașov County Public Service), local administrations (Bucharest City Hall), ePtc.

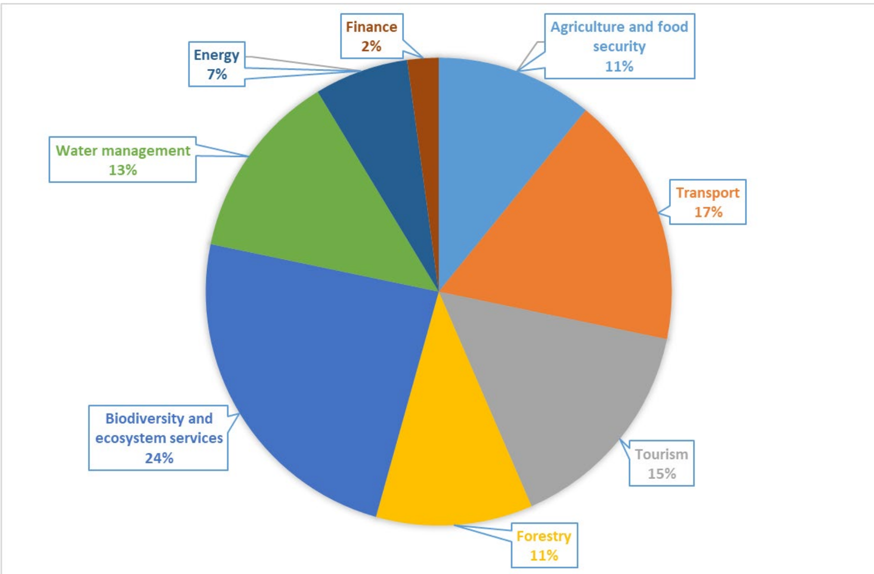

Figure 9. Organisation's activity sector of the relevant stakeholders for CSA#2, #5 and #6 in Romania

Stakeholder's feedback

The stakeholders feedback has been provided both through active discussions and an online survey. More than 60% of stakeholders consider that their sector is high and very high exposed to socio-economic impacts induced by climate change (Fig. 10).

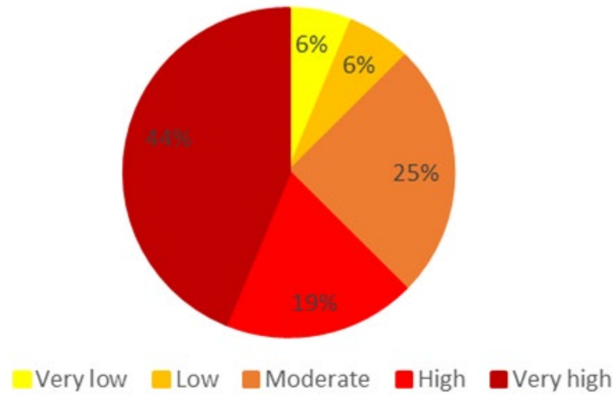

Figure 10. Answers to the question: Is your activity sector subject to socio-economic impacts induced by climate change

The climatic hazards that affect the stakeholders' activities (Fig. 11) are drought and heat waves (>40%) (agriculture, biodiversity, forestry and transport sectors), followed by storms and snow (>30%) (water management, energy and transport). Water management and transport sectors are both affected by all climatic hazards mentioned in the survey.

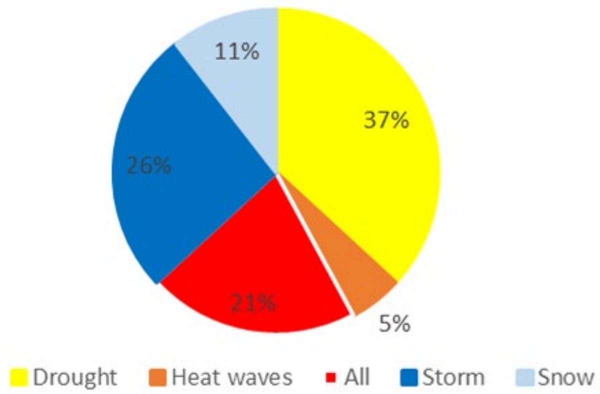

Figure 11. Answers to the question: What are the climatic hazards affecting your organisation's activity?

In the present, only 25% from stakeholders responded that their organisations are using a decision support system (Fig. 12). The sectors that they are representing are water management, energy and biodiversity. All stakeholders confirmed the necessity of the DSS at the level of their organisations.

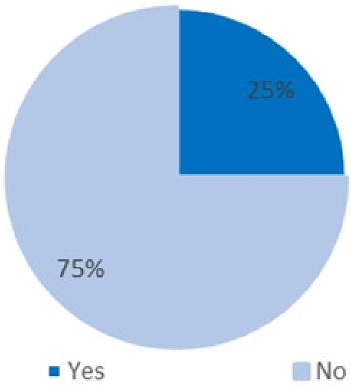

Figure 12. Answers to the question: Is your organisation using a decision support system (DSS) to make decisions?

Stakeholders expressed the interest (Fig. 13) to be involved in co-design (19%) and testing activities (31%), while 31% declared that they agree to be informed. Just a low percent (6%) of stakeholders is not interested to be engaged within CROSSEU project.

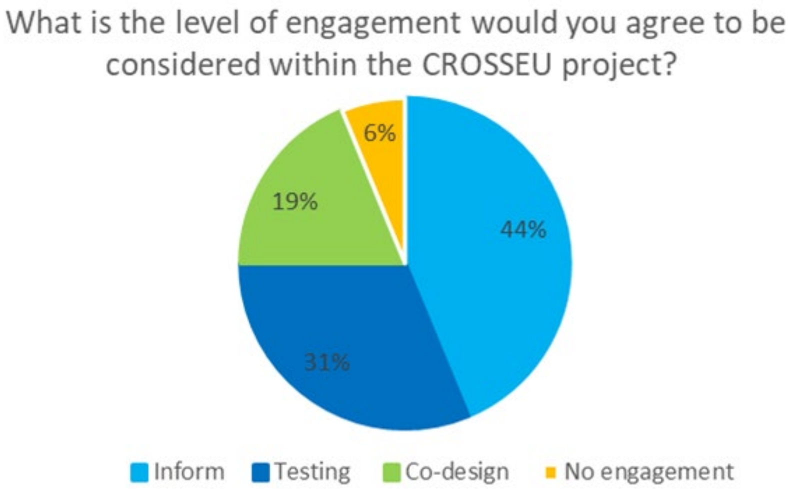

Figure 13. Answers to the question: What is the level of engagement would you agree to be considered within the CROSSEU project?

4.4.3. The 1st CROSSEU stakeholder engagement co-design workshop in CSA#1 Heat – Czech Republic

About the event

The Workshop was held online on 25th March 2024. Twelve stakeholders participated in the first workshop in CSA#1 - Czech Republic, including professionals from biometeorological forecasting and national public health institute, researchers from academia collaborating on similar projects and/or adaptation strategies and representatives of regions and municipalities who have been involved in climate adaptation strategies for their cities/regions.

Participants from the Czech Republic:

- Technical University Liberec – assistance with climate adaptation plan in health sector of Liberecky kraj (a NUTS 3 region);
- City Jablonec nad Nisou – climate adaptation strategy for the city, preparation of the climate adaptation strategies, its impact on public health;
- National Public Health Institute – involved in the National Climate Adaptation Plan - health
- Prague (municipality) – collaboration on the climate adaption strategy of the city of Prague;
- Czech Hydrometeorological Institute (CHMI) – coordinator of the biometeorological forecasting for the Czech Republic;
- Liberec (municipality) – preparation of adaptation strategies for the city;
- Insitute of Computer Sciences, Czech Academy of Sciences - involved in several national and EU projects focusing on climate services, climate adaptation strategies e.g. CARMINE - potential collaboration on particular tasks of the project;
- Charles University, Faculty of Mathematics and Physics – involved in several national and EU projects focusing on climate services, climate adaptation strategies e.g. Impetus4Change (https://impetus4change.eu/), FOCI (https://www.project-foci.eu/wp/) – potential collaboration on tasks of the project.

Stakeholder's feedback

Stakeholders from the Czech Republic are involved in health, climate change and adaptation and weather forecast sectors. They consider that heat is the main climatic hazard that affect their organisation's activity. Their organisations are not using a decision support system to make decisions and they do not consider beneficial the use of a DSS in their activity. The declared level of engagement for most of the stakeholders is consultation. Representatives of the City of Prague and Charles University have expressed the interest to be actively engaged in the development of the plan together (co-creation) with the project team.

4.4.4. The 1st CROSSEU stakeholder engagement co-design workshop in CSA#3 Storm – Denmark

About the event

The Workshop took place online, on the 31st of May 2024. Five stakeholders from the Association of Danish Municipalities, Sønderborg and Aabenraa municipalities attended the 1st workshop in CSA#3 - Denmark. The workshop focused on introducing the primary stakeholders to the aim and objectives of the CROSSEU project, and more specifically to the content of the CSA#3 on storms in Denmark and Germany. The overall aim was to discuss the expected involvement of the stakeholders in the different stages of the work/analysis that is to take place, to gain insight from them on their expectations to their involvement, and to the different outputs of the analyses conducted as part of CSA#3. Also, the organisers discuss how they can get access to some of the local socioeconomic data. Finally, the meeting was used to agree on a field trip to visit some of the flood prone areas in Sønderborg and Aabenraa together with the stakeholders. The field trip will take place in Q4 2024.

Stakeholder's feedback

All the involved stakeholders are very interested in getting involved in the project and can see a huge benefit of being deeply involved in the analyses as part of the case study. Data collection from the individual municipalities and from KL is possible. The focus is to gain access to local socio-economic data, and to damage-cost data collected in the aftermath of the October 2023 storm surge. The field trip was agreed to take place in Q4-2024. The dates for the field trip will be decided before summer 2024.

4.4.5. The CROSSEU Stakeholder Engagement Co-Design Workshop – Europe

About the event

The event took place online on April 22, 2024. Forty-three stakeholders from different organisations and sectors (agriculture, water management, civil protection, transport, health, biodiversity, energy and migration) from Europe attended this workshop. In the first part of the meeting, the CROSSEU project's general information and objectives have been presented to European stakeholders. Then, the case studies and the DSS concept were presented, and stakeholders were informed that they will be engaged in the co-creation of the DSS platform. The last part of the meeting was dedicated to interactions with stakeholders guided by a set of questions targeted to identify their requirements. At the end of the workshop, stakeholders were invited to fill in a feedback form.

Participants from Europe

The workshop organised at European level targeted the relevant stakeholders from all sectors selected within the CROSSEU project. Participants belong to the following sectors (Fig. 14): biodiversity and ecosystems services (21%), agriculture and food security (12%), energy (12%), health (12%), transport (10%), water management (9%), civil protection (7%), disaster risk reduction (5%), migration (5%) and social research (2%).

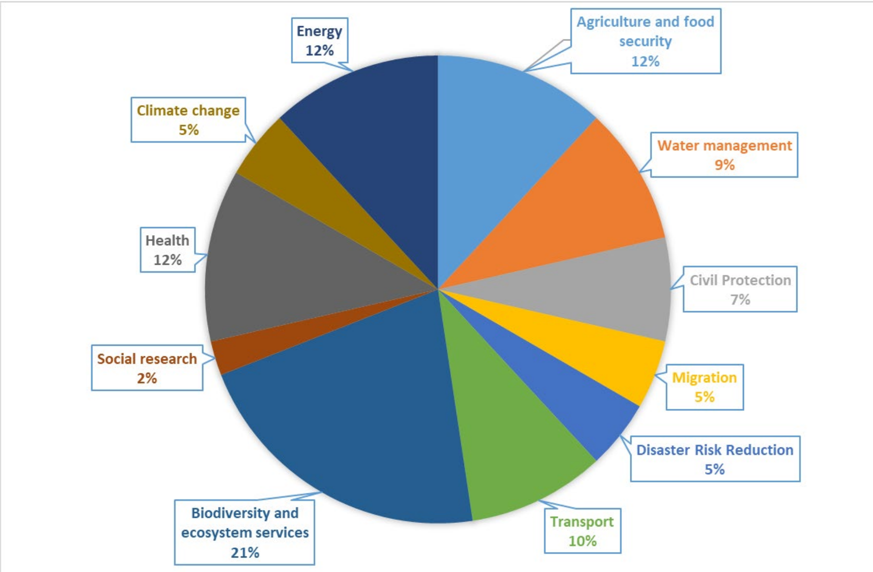

Figure 14. Organisation's activity sector of the relevant stakeholders from Europe

Stakeholder's feedback

The preliminary stakeholder's feedback has been received during the discussions generated in the last part of the workshop. All climatic hazards addressed into the project present interest for stakeholders, but heat stress and risks in large metropolitan areas and droughts that affect the hydropower sector received more attention. Few concerns have been risen by stakeholders:

- How the results of the project related to heat stress and risk assessment will be made known to vulnerable groups;
- How to address potential droughts in hydropower sector;

The first concern will be overcome in the CROSSEU project by producing new climatic and health data at fine scale, considering the most vulnerable groups, and by collaboration with local administrations at the level of cities selected into the project.

The second concern will be addressed by using models that consider both floods and low flows.

At the end of the workshop, stakeholders were informed that they will be kept up to date with the progress of the project and will be invited to participate to the next European workshop where they will be able to express their interest on how to design the DSS platform according to their specific requirements.

4.4.6. Conclusions

The workshops organised both at national and European scales allowed to collect first feedback from the stakeholders on the project objectives and expected results, as well as stakeholders' priorities, common goals and the desired level of involvement and communication channels.

In Italy, the stakeholders selected for CSA#4 expressed their availability to contribute to the co-generation of impact scenarios and to host pilot actions that may be carried out within CSA#4 activities, to co-develop the DSS platform and to test it. In addition, they offered to provide specific data that may be needed for CSA#4 activities.

In Romania, the stakeholders selected for CSA#2, #5 and #6 confirmed the necessity of the DSS at the level of their organisations. Stakeholders expressed the interest to be involved in co-design (19%) and testing activities (31%), while 31% declared that they agree to be informed.

In Czech Republic, stakeholders selected for CSA#1 consider that heat is the main climatic hazard that affect their organisation's activity. Their organisations are not using a decision support system to make decisions and they do not consider beneficial the use of a DSS in their activity. The declared level of engagement for most of the stakeholders is consultation. Just Charles University has expressed the interest to actively work on the development of the plan together (co-creation) with the project team.

In Denmark, stakeholders are very interested in getting involved in the project and can see a huge benefit of being deeply involved in the analyses as part of the case study. Data collection from the individual municipalities and from KL is possible. The focus is to gain access to local socio-economic data, and to damage-cost data collected in the aftermath of the October 2023 storm surge.

The next steps will consist to maintain the link with both national and European stakeholders, to inform them about the progress of the project, to establish continuous feedback and to invite them to participate to the next European workshop where they will be able to express their interest on how to design the DSS platform according to their specific requirements.

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