Deliverable D1.2 - *Desk review of existing CRA frameworks*

WP1 – Framework for local and regional climate risk assessment

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(Grant Agreement 101093864)

HORIZON-MISS-2021-CLIMA-02-01 - Development of climate change risk assessments in European regions and communities based on a transparent and harmonised Climate Risk Assessment approach

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About CLIMAAX

CLIMAte risk and vulnerability Assessment framework and toolboX (CLIMAAX) is a 4-year Horizon Europe project that will provide financial, analytical, and practical support to improve regional climate and emergency risk management plans. The project started in January 2023 and runs until December 2026. The main objective of CLIMAAX is to support the implementation of the EU Adaptation Strategy and the Mission Adaptation first objective: preparing and planning for climate resilience. CLIMAAX will co-design a harmonized methodological framework to assess the climate change risks and impacts at the regional scale across Europe. This framework will be supported by an operational multi-risk assessment methodological framework and supporting Toolbox to assist regions and communities in better understanding, preparing for and managing climate risks. The framework and Toolbox will be implemented in >50 EU Regions/Cities/Communities allowing the demonstration and beta testing of the climate risk and vulnerability assessment framework Toolbox, the refinement of the assessment tools, and the enhancement of the adaptive capacity of European regions and communities to reduce their vulnerability to climate change.

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Document History

Deliverable Title	Desk review of existing CRA frameworks
Brief Description	Deliverable 1.2 conducts an extensive desk review of relevant EU-focussed and international publications on climate risk assessment frameworks. It identifies relevant processes as well as focusses on key principles and choices in order to feed into CLIMAAX thinking for developing a framework that can be widely applied to regional risk assessments.
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Lead Beneficiary	IIASA
Author(s)	Bachmann, M., Higuera Roa, O., Mechler, R., Šakić Trogrlić, R., Reimann, L., Mazzoleni, M., Sestito, B., Buskop, T., Mysiak, J., Pirani, A., Pal, J., Aerts, J.
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Executive Summary

The objective of Deliverable 1.2 (D1.2) is to review relevant literature on Climate Risk Assessments (CRAs) and frameworks, aiming to finally support the development of a shared, inclusive, and harmonized framework that can benefit not only the CLIMAAX project regions but also other beneficiaries. This deliverable provides an overview of concepts, current developments and gaps in the field of CRA, thus setting a baseline for further work in the CLIMAAX project. Overall, we find that CRAs are not consistently applied in Europe across scales, leading to a fragmented understanding of climate risks. The current assessment of climate risks varies in terms of levels, scales, and forms, lacking cohesion and posing challenges for regions, local governments and communities.

The current understanding of climate risk is shaped by the Intergovernmental Panel on Climate Change (IPCC). According to IPCC's 6th assessment report risk is defined as the dynamic interaction between hazard, vulnerability, and exposure in human and natural systems, with responses added as a fourth element of this so-called "risk propeller", thus highlighting the need for a consistent multi-disciplinary approach for CRA. Aligning to this definition, the International Organization for Standardization (ISO) provides guidance to assess vulnerability, impacts and risks related to climate change, including principles and good practices through the publication of the ISO 14091.

Various frameworks have been developed to organize the risk assessment. Mostly these frameworks suggest to integrate CRA with assessments of current and future risk management or adaptation options to support decision-making. Generally, such frameworks follow a cyclical and iterative process from risk assessment to supporting risk management. Lately, the literature has been emphasizing to start with a clear system definition (ideally current and future) and respective stakeholders to be involved from the outset, before proceeding with actual risk estimation.

The scientific literature on CRA has embraced IPCC's risk understanding over time, initially considering hazard, exposure and vulnerability to later include responses in the analysis. However, the field of CRA is continuously evolving, and new concepts and frameworks are gaining momentum. Climate hazard studies have transitioned to a multi-hazard approach, while the various forms and dynamics of exposure and vulnerability have advanced new studies to understand risks better. More recently, the recognition that climate risks can also arise from climate responses and the consideration of previously overlooked and potentially time-varying factors like risk perception, risk tolerance, cascading effects, and cross-sectoral impacts is pushing the boundaries in the field. This reflects a shift towards a more complex and systemic understanding of climate risks.

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However, as knowledge advances, new gaps emerge. These include the need for better understanding multi-risks, risk dynamics, societal dimensions (such as behavior and normative choices), and the continuous need for tackling the various uncertainties associated with CRA.

Policy-planning documents including national risk assessments done for the European Union Civil Protection Mechanism (UCPM), national adaptation plans and strategies (NAPs/NAS) as well as Sendai Mid-Term reviews (MTR) help to understand if and how the concept of climate risk and climate risk assessment has found its way into practice and what gaps remain to be tackled. The reviewed documents show a very heterogenous level of consideration, conceptualization and application of climate risk with some examples demonstrating a more advanced understanding, however, overall clearly limping behind the scientific developments. This is especially the case for NAPs and NAS. While the UCPM national risk assessments and Sendai Mid-Term reviews are more explicitly risk-centered by nature, NAPs and NAS are not per se built on a risk-based approach.

National risk assessments for the UCPM cover hazard threats (e.g. technological, anthropogenic, geo-/ecological, etc.) similar to Sendai MTRs, however not necessarily with a clear climate risk focus. Also, both document types provide insights into collaboration mechanisms for (disaster) risk management between national and subnational organizations or stakeholders, which generates an important impetus for the establishment of a CRA framework and toolbox.

The NAPs and NAS show significant variation in risk considerations and conceptualizations as a basis for adaptation options. While the reviewed documents are usually not directly tied to CRAs, many plans and strategies show examples of good practice related to CRA. Also, the more practical considerations of risk management in MTRs and UCPM risk assessments are contrasted with top-down and bottom-up risk governance aspects in NAS and NAPs. Overall, there is rising awareness of the importance of conducting regional and local (municipal) risk assessments, which is however only partially enforced to date leading to a fragmented risk landscape.

All documents show that there is the need for a harmonized risk approach with a shared risk conceptualization. Also, the issue of data availability and processing is not only encountered in practice, but also remains a big challenge to be overcome by the scientific community. To this effect, by developing such a harmonized climate risk framework together with a data-driven toolbox based on state-of-the-art literature and latest scientific developments, the CLIMAAX project will eventually be able to support selected European regions in their climate risk assessments based on well understood needs and current scientific progress.

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1. Introduction

With climate change increasingly affecting people, assets and the environment, Climate Risk Assessment (CRA) is seeing strong attention for understanding the scope and scale of climate risks in order to plan and implement emergency response and adaptation responses. Effectively carrying out CRA depends on various factors, such as the purpose of the exercise, the system to be assessed, expertise of the assessment team, local and global data at hand, climate models to be used, etc. To harmonize CRA practices and promote mutual learning by exchange of experiences, a framework based on international standards and established scientific literature as well as good-practice examples is useful.

To this effect, the objective of Deliverable 1.2 (D1.2) is to review relevant white and grey literature on climate risk assessment in order to eventually support the development and application of an inclusive, harmonized and shared framework for climate risk assessment to be developed in D1.4 and to be applied further in CLIMAAX. The deliverable identifies relevant processes as well as key principles and choices within the context of CRA, which will feed into the CLIMAAX framework and toolbox so that it can be widely applied to support the execution of a collection of regional risk assessments. While D1.2 focusses strongly on conceptual and procedural issues, D2.1 in WP2 presents the development of the risk assessment toolbox with technical detail for computing various climate risks at regional scales.

The Deliverable is organized as follows: We will first discuss how the evolution of the risk concept and frameworks from climate vulnerability to climate risk has taken place in the field and what risk standards have evolved. This is then followed by detailed reviews of CRA application and development for different purposes, sectors and regions including (i) trends, practices and risk-related issues that have been emerging in peer-reviewed literature, and (ii) the role of risk assessments in national and regional documents. Special emphasis lies on the evolutionary and converging aspects of risk in the literature by assessing existing frameworks, processes and objectives for CRAs. To this effect, D1.2 conducts an extensive desk review of CRA relevant literature, which goes beyond the perspective of risk assessments by including a broad spectrum of publications and grey literature. This includes (i) a discussion of concepts and overall considerations in section 2, (ii) an EU-focused **peer-reviewed literature review** in section 3.1 to gather risk-related information and then summarized in the respective sections; (iii) While the peer reviewed literature dives deep into some concepts, developments and challenges of CRAs from a science and evidence-based perspective, 3.2. and 3.3. provide overviews of risk-considerations in national and international documents with good practice examples, including in section 3.2. an overview of the literature of the **Union Civil Protection Mechanism (UCPM**) with national/regional risk assessments in the projected pilot regions, thus

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focusing on risk-related applications of UCPM; section 3.3 discusses CRA for **national adaptation plans and strategies** as well as Sendai Mid-Term reviews.

Overall, the findings of this deliverable emphasize the urgent need for supporting climate adaptation at regional levels by performing state-of-the-art climate risk assessments tailored to the needs of relevant stakeholders, building on a comprehensive climate risk framework and combining with a flexible toolbox infrastructure to support the use of relevant data and outputs for the regions that are undertaking assessments.

2. Concepts and overall considerations

2.1. Evolution from Climate Vulnerability to Climate Risk

Climate impacts, vulnerability and risk research and applications are decades old and have undergone conceptual change and development as closely followed and assessed by the IPCC. Originally focused on understanding physical impacts through interacting exposure and sensitivity of biophysical systems, concern for social systems' impacts, and awareness that social systems have capacities to adapt to impacts deliberately and resourcefully, the concept of (social) vulnerability has seen attention to assess which regions, countries or sectors may be vulnerable in a changing climate. Defined as the "propensity or predisposition to be adversely affected" (IPCC, 2009) and determined by the outcome of exposure, sensitivity and adaptive capacity, vulnerability has often been operationalized by a host of indices, and the field has emphasized how processes leading to vulnerability develop.

Over the years, with climate impacts becoming increasingly evident and associated with more tangible consequence, the significance of actual and potential socio-economic impacts has moved to the forefront, and overlaps of climate science and disaster risk research and practice have become more apparent. To some extent building on disaster and other risk research, the focus on vulnerability has been replaced by one on *risk*, where risk creation is considered a function of exposure, current and future hazards, and vulnerability; and risk outcome is often measured by the probability of physical and social impacts occurring. The inclusion of vulnerability into risk assessments and the shift towards a risk-focused approach in research and practice is meant to be more actionable for decision-makers and practitioners. This shift has been well documented in IPCC's 5th assessment cycle with the publication of the SREX[1] report in 2012 (IPCC, 2012) and the 5th assessment report (AR5) in 2014 (IPCC, 2014) (see Figure 1).Since the transition from vulnerability to risk assessments, CRAs have received increasing attention, development, and implementation across various scales, sectors, regions, and communities (Ara Begum *et al.*, 2022).

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[1] SREX stands for “Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.”

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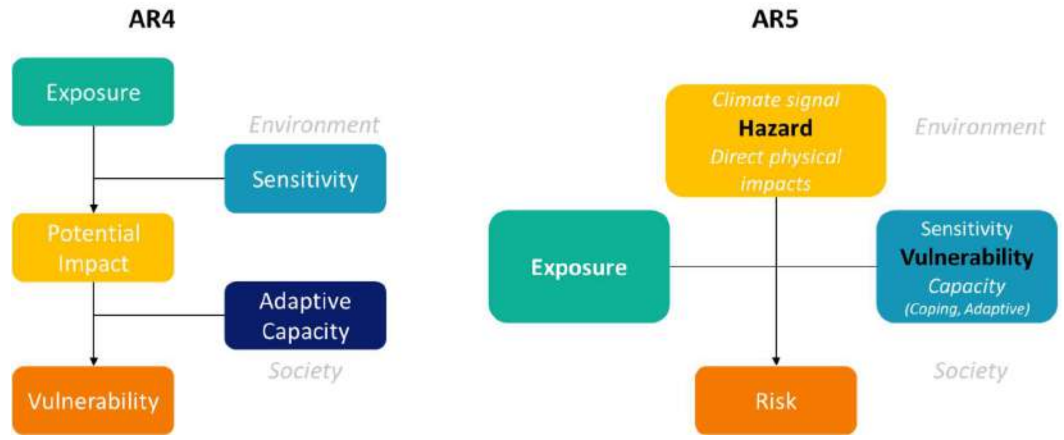

Figure 1. The shift of concepts from climate vulnerability to climate risk as documented by IPCC 4th and 5th assessments (GIZ and Eurac Research, 2017).

2.2. Current IPCC understanding of Climate Risks

The risk-focused framing is currently ever more strongly embedded in the IPCC's 6th assessment cycle (AR6), building on the earlier SREX "Risk Propeller Framework" (IPCC, 2012) by adding adaptation (and sometimes mitigation) responses into the "risk equation" (Figure 2).

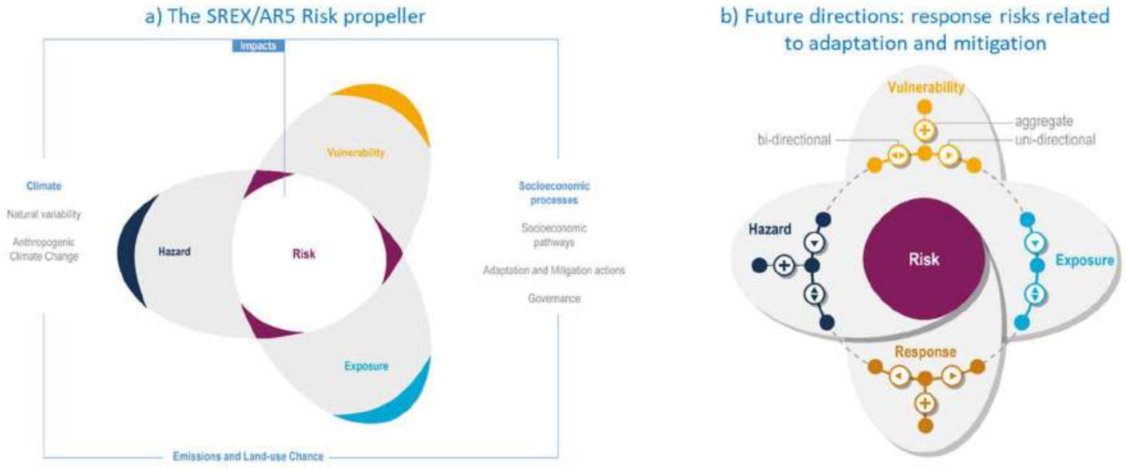

Figure 2. Original IPCC 'risk propeller' and amended version with responses added (Ara Begum et al., 2022).

The AR6 understanding of risk (see Box 1), defines risk as the dynamic interaction between hazard, vulnerability, and exposure of human and natural systems (Reisinger *et al.*, 2020), and responses (Ara Begum *et al.*, 2022), highlighting the need for a consistent multi-disciplinary approach for CRA.

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Box 1. The current IPCC understanding of risk.

IPCC framing of risk in IPCC's 6th assessment cycle

The **potential for adverse consequences** for human or ecological systems, recognising the **diversity of values and objectives** associated with such systems. In the context of climate change, **risks can arise from potential impacts** of climate change **as well as** human **responses to climate change**. Relevant adverse consequences include those on lives, livelihoods, health and wellbeing, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species. (Reisinger et al., 2020, p. 4)

Risk emerges from the combination of social processes and their interaction with the environment (hazards and stressors) (IPCC, 2012, 2022b). This definition recognizes that risk is not fixed but constantly evolving and influenced by changes in hazards, vulnerability, and exposure due to climatic and socioeconomic factors (IPCC, 2012; Reisinger *et al.*, 2020; Chen *et al.*, 2021; Ranasinghe *et al.*, 2021). Also, the inherent complexity of climate risk is acknowledged, which includes feedbacks, cascades, non-linear behaviour and the potential for surprise (Ara Begum *et al.*, 2022). Whether these changes are natural, unintended, or deliberate, they contribute to the dynamic nature of risk (Reisinger *et al.*, 2020).

Anthropogenic climate change, natural climate variability, and socioeconomic development all play significant roles in shaping risks, exposure, and vulnerability (IPCC, 2012; Field *et al.*, 2014). Changes in the climate system and socioeconomic processes, including adaptation and mitigation efforts, act as drivers of hazards, exposure, and vulnerability (Field *et al.*, 2014; Ranasinghe *et al.*, 2021). In that sense, risks can also arise from the potential failure of responses to achieve their intended objectives or from trade-offs and negative side effects on other societal objectives (Reisinger *et al.*, 2020). Consequently, not only climate change, through its impact on hazards, exposure, and vulnerability, generates risks and impacts that can surpass the limits of adaptation and result in losses and damages (IPCC, 2022b); also poorly planned and mismanaged climate responses can add to the burdens.

It is worth mentioning that the terminology used in the AR6 evolved from the previous SREX report, with "weather and climate events" and "disaster risks" now referred to as "climate hazard" and "risk," respectively. Thus, in the context of the IPCC reports, risk specifically refers to climate change impacts (Field *et al.*, 2014), focusing on adverse effects and risks induced by shifts in physical climate phenomena that directly influence human and ecological systems (Ranasinghe *et al.*, 2021).

Importantly, the AR6 definition of risk emphasizes the potential for adverse consequences, referring to only negative consequences (Reisinger *et al.*, 2020), based on the main objective of the United

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Nations Framework Convention on Climate Change (UNFCCC) which is to “prevent dangerous anthropogenic interference with the climate system” (Ranasinghe *et al.*, 2021). In addition, the AR6 acknowledges the diversity of values and objectives in assessing risks, considering that different individuals will evaluate the potential consequences for human and ecological systems from various perspectives: material, cultural, spiritual, economic, or ecological (Reisinger *et al.*, 2020), or contribute to their restoration and conservation.

2.3. Objectives and principles associated with CRAs per international standards

While IPCC's objective is foremost to assess the state of the art of climate science, it also contributes to standard setting directly and indirectly. Yet, it is the specific purpose of **the International Organization for Standardization (ISO**), a federation of national standard bodies, to work towards international standard setting by developing relevant guidance documents that follow ISO procedures and thus contribute to standard setting in national and international contexts. To this effect, ISO 14091 (ISO, 2021) develops guidance on vulnerability, impacts and risk assessment supporting adaptation in various systems generally, while ISO 14090 and 14092 (ISO, 2019, 2020) are meant to support adaptation planning generally (14090) and specifically for local governments and communities (14092). Systems may be associated with public or provide sectors and constitute "a region, a community, a household, a supply chain, an economic sector, a business, a population group, an ecosystem, infrastructure and its components" (ISO, 2021 p. 4).

In terms of concepts and definitions the complementary ISO documents largely overlap with IPCC, and ISO also proposes to follow the IPCC framing of risk (*risk propeller*).

ISO 14091 defines **four objectives for CRAs: (1) Raising awareness, (2) identification and prioritization of risks, (3) identification of entry points for climate change adaptation interventions and (4) tracking changes in risk**, as well as **monitoring and evaluating adaptation actions** that have been implemented.

ISO 14092 suggests several principles to adhere to, which align with **good assessment practices**. The following seem particularly important for CRA purposes:

- **Accountability -** local level acknowledges and assumes responsibility for their climate change risks and possible adaptation actions.
- **Continual learning and improvement -** in a context of changing risk and information.
- **Flexibility of assessments -** considering relevant technical, social, administrative, political, legal, environmental and economic circumstances given large variability in quantity and quality of data as well as regarding availability of technical and institutional capacities to assess risks

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When **preparing** for CRA for informing adaptation, ISO 14091 suggests, among others, the following sequential actions ought to be taken:

- **Establishing the context** and associated considerations: system at risk, time horizon, hazards to be considered, processes linked to risk assessment (e.g. supply chains), knowledge to be used, parties to be consulted, resources available and any regulatory obligations to observe.
- **Defining objectives** and projected **outcomes** of the assessment.
- Determining an appropriate **methodology**, including considering transparency with regard to process and uncertainty assessment, participation of relevant parties and stakeholder involvement, and awareness for value judgments (necessary in certain instances).

For **implementation**, the following principles and actions are highlighted:

- **Screening** relevant impacts and processes in and across systems within and across regions.
- Considering aspects of **representativeness, replicability and feasibility** (of assessment) for relevant impact/risk indicators,
- Using **various methods for data generation**, including measurement, censuses and surveys, modelling and value judgments, as well as for future data, scenario information (such as IPCC's RCP/SSP database) including projections and sensitivity analyses ought to be used.
- **Aggregation techniques** to be considered, such as weighting, normalization, and visual overlays.
- **Checks** on data quality to be undertaken and employing independent review, where feasible.

2.4. Frameworks

Various frameworks have been developed to organize the risk assessment. Mostly, CRAs are integrated with assessments of current and future risk management or adaptation options to support decision-making (see ISO, 2021).

For example, guidance by UNDRR (2022) shows how the different components of risk may be integrated to a comprehensive estimate of risk that for a specific context and objectives supports the identification, prioritization, implementation and monitoring of measures (Figure 3).

Generally, such frameworks follow a cyclical and iterative process from risk assessment to supporting risk management (ISO, 2021). Lately, as shown in Hochrainer-Stigler et al. (2023), the literature has been emphasizing to start with a clear system definition (ideally current and future) and respective stakeholders to be involved, before proceeding with actual risk estimation (Figure 4).

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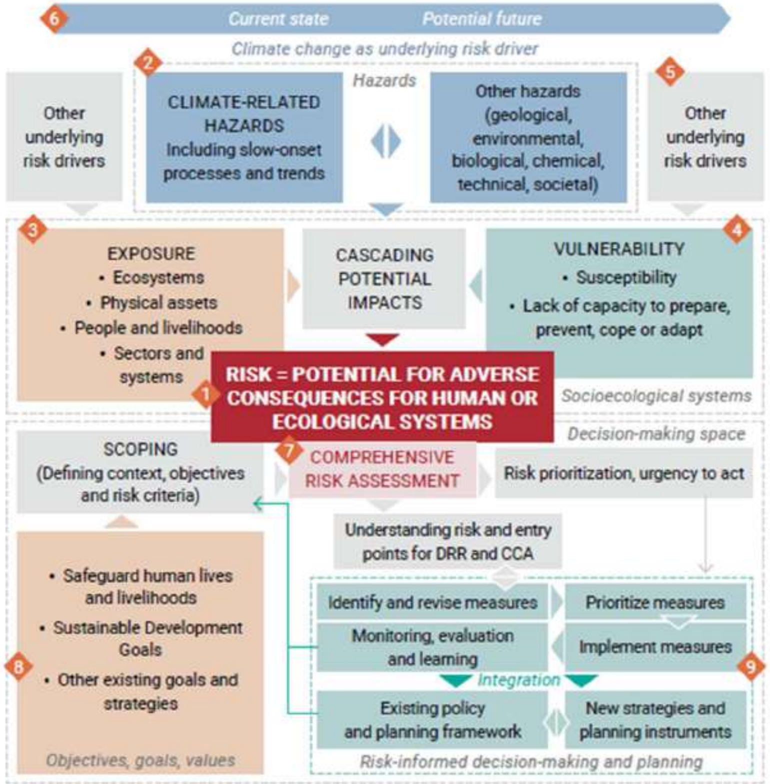

Figure 3. UNDRR guidance on risk assessment and management (UNDRR, 2022).

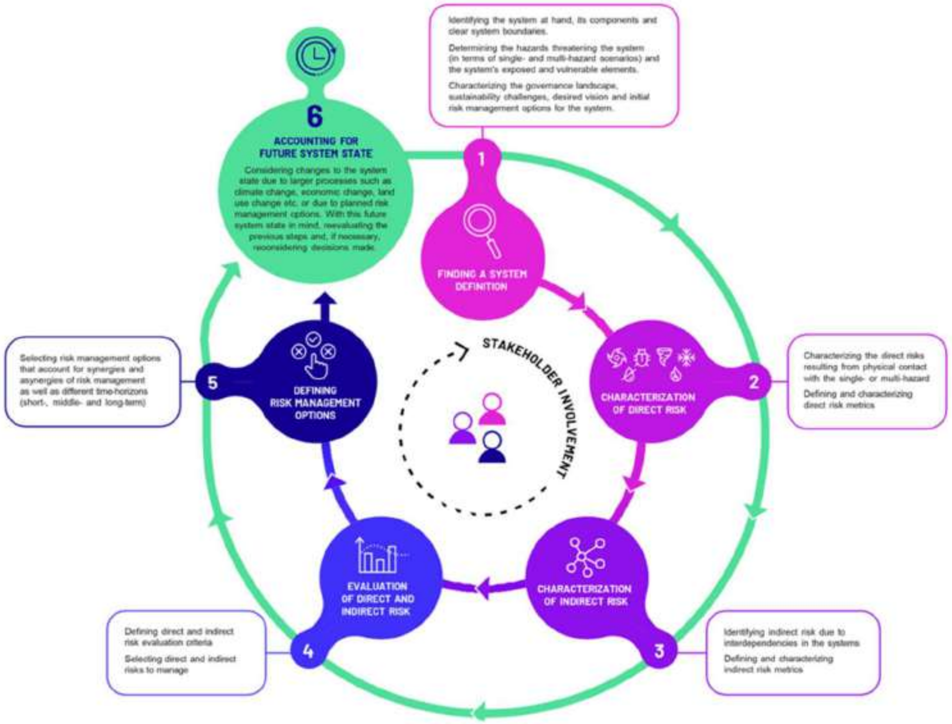

Figure 4. Myriad risk assessment framework (Hochrainer-Stigler et al., 2023).

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3. Review of relevant CRA literature

Building on the general considerations discussed above, we now assess the state-of-the-art and application of CRAs as used for different purposes, systems, regions etc. as documented in the grey and white literature including in

- Peer-reviewed literature on climate risk assessment (3.1.)
- National and regional risk assessments and Union Civil Protection Mechanism (3.2.)
- Risk assessments for national and international policy dialogue (3.3.)

3.1. Peer-reviewed literature on climate risk assessment

This section provides an overview of relevant conceptual and operational aspects of climate risk assessment building on established to recent peer-reviewed literature (2010-2023).

3.1.1. Relevant and emerging concepts in climate risk analysis

CRA is a constantly evolving field, and so is the societal demand for better CRA. CRA helps national and local governments to identify, plan and implement climate risk mitigation measures. The development of new scientific methods to analyze climate risks along with the urgency to address the climate crisis in the international policy agenda (e.g. Sendai Framework, Paris Agreement) have promoted the development of the CRA field.

With the progression of the field there are several emerging concepts and frameworks that are raising attention. One of those is the framework for **Complex Climate Risks** proposed by Simpson et al. (2021). This framework introduces three categories of increasing complexity: single driver interaction, multiple driver interaction, and interacting risks. Notably, as discussed above the authors argue that risks can arise from responses to climate change, not just from the influence of climate change on the conventional risk propeller (hazard, exposure, and vulnerability) (IPCC, 2012, 2014). This is in line with Terzi et al. (2019), who also support the idea that maladaptation practices can increase risks. However, generally well-planned and implemented adaptation practices have been found to be a cost-effective way to reduce climate risk (Chambwera *et al.*, 2014).

A second concept, introduced by Ruane et al. (2022) and adopted in the IPCC AR6 (see Chen *et al.*, 2021), is that of **Climatic Impact-Drivers (CID),** which broadens the evaluation of physical climate conditions (averages, events, and extremes) influencing human and natural systems. The authors argue that depending on the system's tolerance, climatic conditions can have diverse effects, ranging from detrimental to beneficial, neutral, or even mixed, across different interacting system elements, regions, and sectors of society. Additionally, the CID concept augments the understanding of physical climate conditions by recognizing that multiple sectors can be influenced by various CIDs,

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and each CID can have an impact on multiple sectors that can be considered either hazards when associated with risk, or boons when associated with benefits or opportunities.

The third concept deals with **event-based storylines** discussed by Sillmann *et al.* (2021) as an alternative to probabilistic climate change models (also see Shepherd *et al.*, 2018; van den Hurk *et al.*, 2023). Storylines try to circumvent event probabilities since high-impact events are often challenging to quantify with a specific probability due to their rarity and uniqueness (Zscheischler, Westra, Van Den Hurk, *et al.*, 2018). Instead, storylines focus on the interaction of the driving factors and interactions that cause impacts (Shepherd *et al.*, 2018). Here, addressing climate risk is based on "plausibility, salience, and relevance" (Sillmann *et al.*, 2021, p. 4), thus already including vulnerability and exposure considerations by combining physical and human facets of climate change. Further, by subjecting past weather events to climatic, socio-economic or policy changes it is possible to gain insight into impacts and dynamics of hypothetical events, called 'counterfactuals' (Ciullo *et al.*, 2021).

Despite both approaches having their advantages and limitations, a combination of probabilistic and storyline approaches is possible (Brusselaers *et al.*, 2023). While the probabilistic approach is especially useful for e.g. risk financing and cost-benefit analysis, the storyline approach can reveal the complexities of natural hazard events both in terms of direct and indirect impacts of various risk bearers. Therefore, constructing storylines comprising uncertain events and emerging impacts can provide novel system insights that might be missed in a probabilistic approach and may give meaningful inputs for stakeholders in a decision-making process.

Several other concepts, some with more traction than others, have also been emerging in the CRA field. For instance, concepts such as risk tolerance, threshold values (for hazards)[2], risk dynamics, time of emergence[3], risk quantification (e.g. probabilistic risk assessments for levee systems in the Netherlands; see Jongejan and Maaskant, 2015), and adaptive or coping capacity are relevant for the development of effective and comprehensive CRAs.

3.1.2. Current operationalization of the risk concept and its components

The *current implementation of the risk concept and its components in CRA in peer-reviewed literature* complements the ISO 14091 standard and the IPCC risk understanding with further insights regarding the four risk propeller components *hazard*, *exposure*, *vulnerability* and *response*. The fifth aspect, *impacts*, aims to provide context to the consequences of climate risks (indirect, cascading,

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[2] Threshold for hazards represent specific values (e.g., magnitude, duration, frequency, timing, and spatial extent) at which a climate condition interacts with vulnerability and exposure to generate, amplify, or diminish impacts, risks, or in some cases, unlock opportunities (Ranasinghe *et al.*, 2021).

[3] When climate signals trespass thresholds in a given geographic area and become apparent, having significant implications for assessing risks and their economic and transboundary effects (Challinor *et al.*, 2018; Ignjacevic, Estrada and Botzen, 2021).

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and compounding effects) on ecosystems, people, and infrastructure. This section proceeds to discuss operationalization aspects of key elements of the risk concept including hazard, vulnerability, exposure and responses.

A. Hazards: towards a multi-hazard perspective

Hazard assessment is essential for understanding the potential intensity, frequency, and spatial distribution of climate-related events such as floods, heatwaves, droughts, and storms. These events can have significant consequences for human health, food security, water resources, and infrastructure (IPCC, 2012). Furthermore, hazard assessment plays a key role in the development of sustainable adaptation and mitigation strategies, as well as emergency responses (National Research Council, 2010). Improved hazard assessment frameworks, including the use of advanced climate models and high-resolution remote sensing data, can help decision-makers better understand climate risks (Dottori *et al.*, 2018).

Natural hazard events are random in nature and therefore probabilistic approaches are considered as the most appropriate for the analysis of such (Hochrainer-Stigler *et al.*, 2023). Usually, probabilistic assessments are carried out through (statistical) analysis of past events or by building weather generators that can simulate natural hazard events. The definition of extremes is then mainly based on statistical risk measures such as quantiles, averages, or threshold levels (Grossi, Kunreuther and Patel, 2005). One assumption of such approaches to assess, measure and model current hazard is stationarity of the past which often cannot be assumed for the future. Hence, for future hazards non-stationarity, e.g. due to increases in temperature levels, should be explicitly taken into account. Due to the large uncertainties that exists in such models non-probabilistic approaches are now also used as well, including those building on storylines (van den Hurk et al. 2023; see above discussion).

Different approaches have been pursued to develop a **hazard definition**. Some frameworks provide a hazard classification for a **specific typology**. For example, Oppenheimer et al. (2014) classified hazards into floods/precipitation, droughts, heatwaves, cold spells, wind, landslides, coastal hazards, wildfire, water scarcity, etc. Kaspersen & Halsnaes (2017) proposed an integrated climate change risk assessment specific to precipitation and flooding, while Lissner *et al.* (2012) developed a standardized vulnerability assessment specific for heatwaves. Another classification method is **grouping hazards** as intensive or extensive events (Lam and Lassa, 2017). Extensive events are broad scale, gradual changes like droughts, sea level rise and gradual temperature increases. Intensive events refer to extreme occurrences like heavy precipitation, heat waves and storm surges. Zebisch *et al*. (2021) proposed an **impact chain approach**[4], for hazard classification in which hazard is the potential occurrence of a physical (meteorological or climate) event or long-term changes in

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[4] Van den Hurk *et al.* (2023) also address cascading impact chains via a climate event storyline, according to which remote climatic hazards can be connected to (socio-economic) impacts.

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weather and climate conditions that can adversely affect natural and human systems (loss of life, injury, negative health impacts, etc.). Adopting a broader definition of hazard[5], UNDRR and ISC (2020) compiled a comprehensive list of 302 hazards, categorized into eight clusters, which include processes, phenomena and human activities that (i) have the potential to impact a community; (ii) have measurable spatial and temporal components; (iii) with proactive and reactive available measures—thus, the list excludes complex, compound and cascading hazards, as well as underlying disaster risk drivers (such as climate change). Within this context, the publication acknowledges climate change as a key factor contributing to risks but avoids any climate attribution, unlike other systems, by refraining from categorizing some as "climate hazards."

There is a growing interest in **multi-hazard approaches**, analyzing how different hazards coincide, amplify and cascade to generate compound risks (Aznar-Siguan and Bresch, 2019; Parker *et al.*, 2019). Multiple hazards in the context of climate risks can be studied from two different angles: one by investigating how multiple drivers coincide to drive impacts and risks (van den Hurk, White, *et al.*, 2023), and another by analyzing natural hazards of different kinds and their interrelationships in time and space (e.g., triggering, amplifying, independent, compound; Ward *et al.*, 2022). For example, sea level rise exacerbates the impacts of storm surges and coastal floods; droughts increase the risks of wildfires; changes in precipitation patterns lead to both floods and water scarcity. In consequence, the compound impacts of events that overlap, such as coinciding floods and cyclones, are higher than the sum of impacts of individual hazards.

Various frameworks for assessing multi-hazard risks exist. One of the first frameworks for the assessment of risk from compound hazards was proposed by Zscheischler *et al.* (2018); Hochrainer-Stigler *et al.* (2023) provide a recent overview of multi-hazard risk assessment approaches. The multi-hazard approach can provide a more comprehensive analysis of risks in a region (Gallina *et al.*, 2016; Terzi *et al.*, 2019; Simpson *et al.*, 2021), and can lead to better risk management options that account for synergies between risk management measures for individual hazards (De Ruiter *et al.*, 2021). A multi-risk perspective considers both climatic and non-climatic factors (e.g., dynamics of vulnerability and exposure) that interact to generate risks (Lung *et al.*, 2013). In that framing, climatic factors refer to meteorological hazards, while non-climatic factors include environmental degradation, urbanization, socio-economic changes, etc. By recognizing the multiple interacting factors that shape risks the multi-risk perspective becomes useful and relevant for adaptation planning.

To systematically assess risks, it is crucial to properly **characterize hazards**. For example, heatwave hazards can be characterized by the frequency, intensity, and duration of extreme heat events,

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[5] "A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation" (United Nations General Assembly, 2016)

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while drought hazards can be assessed based on deficits in precipitation over time. Some studies have developed hazard metrics and indicators to systematically characterize and rank the severity of climate hazards. For example, Lung *et al*. (2012) used indicators like heat stress, river flood risk, and forest fire risk to represent weather-related hazards in Europe. Torresan *et al.* (2016) utilized hazard metrics such as location, intensity and frequency to characterize coastal hazards. Ronco *et al.* (2017) indexed and quantified the physical impacts of hazards like droughts, heatwaves and floods to assess risks for irrigated agriculture. These hazard indicators and metrics enable hazards to be compared and ranked.

Regarding hazard characterization, many studies have developed **hazard maps** that spatially represent the location and features of hazards. For example, Gallina *et al.* (2020) produced multi-hazard maps showing risks from sea level rise, coastal erosion and storm surge in coastal areas, modelling the spatial distribution of hazards, including future timeframes. Also, some studies (Melo-Aguilar, Agulles and Jordà, 2022; Menk, Terzi, *et al.*, 2022; Zebisch *et al.*, 2022) have used the impact chain approach for tracing how hazards propagate and aggregate through systems to generate risk conditions. Lastly, Machine Learning techniques (Zennaro *et al.*, 2021), Earth Observation imagery (Kotchi *et al.*, 2019), and Big Data approaches (Pollard, Spencer and Jude, 2018) have been applied to improve hazard characterization and forecasting by enhancing real-time detection, prediction and monitoring.

B. *Exposure: assessing different forms of dynamic exposure to climate hazards and identifying hotspots*

The characterization of exposure in current CRAs varies considerably, for example depending on the analysed hazard(s), impacted sectors, and the spatial scale of the assessment. The IPCC definition of exposure[6] is most used in the literature (e.g. Gallina *et al.*, 2016; Adger, Brown and Surminski, 2018; Aznar-Siguan and Bresch, 2019; Simpson *et al.*, 2021; O'Neill *et al.*, 2022), implying that exposure is manifested in the geographical location of different elements potentially at risk from climate hazards (Jurgilevich *et al.*, 2017). Conversely, some studies conceptualize exposure focusing on changing hazard characteristics due to climate change rather than the location of the elements at risk (e.g. Lung *et al.*, 2013; Onyango *et al.*, 2016; Parker *et al.*, 2019; Zebisch *et al.*, 2021).

Exposure is primarily characterized as the population or assets at risk (e.g. Cavan and Kingston, 2012; Lissner *et al.*, 2012; Harrington, Schleussner and Otto, 2021; Simpson *et al.*, 2021; Rising *et al.*, 2022). The indicators that are used to characterize **exposed elements can be hazard dependent**,

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[6] "The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected" (Oppenheimer *et al.*, 2014).

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e.g. with population as the exposed elements for Malaria (Onyango *et al.*, 2016) or heat waves (Lissner *et al.*, 2012), **as well as sector dependent**, e.g. using crop exposure for assessing agriculture risks (Ronco *et al.*, 2017). Challinor *et al.* (2018) consider the impacts of climate change on supply chains and prices in a sectoral climate risk study. In regional- to local-scale CRA, studies also account for a combination of **multiple elements at risk such as environmental resources, physical infrastructure, socioeconomic activities** (Gallina *et al.*, 2020), a variety of different crops (Ronco *et al.*, 2017), or a range of tourism characteristics (Agulles, Melo-Aguilar and Jordà, 2022).

The fact that **exposure is dynamic** has been well acknowledged in recent years (Zscheischler, Westra, van den Hurk, *et al.*, 2018; Kropf *et al.*, 2022; Rising *et al.*, 2022; Ward *et al.*, 2022; Zebisch *et al.*, 2022). Several studies discuss how changes in exposure (and vulnerability) due to socioeconomic development and adaptation responses may influence future climate risks (Gallina *et al.*, 2016; Cremen, Galasso and McCloskey, 2022; Rising *et al.*, 2022), and potentially be a more influential driver of risk than changes in hazard characteristics due to climate change (Gallina *et al.*, 2016; Harrington, Schleussner and Otto, 2021; Menk, Terzi, *et al.*, 2022). These studies suggest a need to better account for future changes in exposure by exploring socioeconomic or land-use change scenarios (Gallina *et al.*, 2016; Cremen, Galasso and McCloskey, 2022), which is still often neglected in current research due to a lack of projections data at scale (Jurgilevich *et al.*, 2017; Menk, Terzi, *et al.*, 2022; Zebisch *et al.*, 2022).

C. Vulnerability: conceptualization of different vulnerabilities

As discussed, based on the IPCC AR5 terminology (Oppenheimer *et al.*, 2014), vulnerability is characterized by the potential of the system to suffer harm or loss when exposed to a hazard. It is a function of the character, magnitude, or rate of climate change and variation to which a system is exposed, including its sensitivity and its adaptive capacity (Zebisch *et al.*, 2021). In this context **sensitivity** determines the degree to which a system is adversely (or beneficially) affected by climate-related stimuli (Warren *et al.*, 2018; Zebisch *et al.*, 2021). Sensitivity “may be determined by (i) natural/physical factors of a system such as ecosystem types, land cover, slope, water holding capacity and erodibility of soils; (ii) natural/physical factors related to human land management activities and infrastructures, such as the existence and quality of dikes, terraces, irrigation systems, houses, roads, electrical grids; (iii) societal factors, such as population density or age structure” (Zebisch *et al.*, 2021). Adaptive capacity refers to the societal characteristics that make a community prepared to face a hazard while it is manifesting and to cope with its consequences and recover after it occurred. It is determined by societal factors such as: economic strength, human skills and education, technology and infrastructure, institutional capability and preparedness (Lung *et al.*, 2013).

While Lung *et al.* (2013) defined **adaptative capacity** as the financial capital (GDP and income equality), human capital (education and health service) and technological capital (research, development,

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internet use), IPCC WGII defined it as "[t]he ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences" (IPCC, 2014). Zebisch *et al.* (2021) explore the adaptive capacity of a society in terms of economic, governance, knowledge, and adaptation options availability, as well as its willingness to actively adapt to climate change and extremes by moderating potential damages, taking advantages of opportunities, or coping with the consequences.

Vulnerability is usually measured in relation to the impact, e.g. through so-called fragility or damage curves (Aznar-Siguan and Bresch, 2019; Kropf *et al.*, 2022). As the impacts of climate related hazards are various and manifest on different sectors, vulnerability is also faceted and varies with the extent or intensity of the considered hazard and the impacted sector (Oppenheimer *et al.*, 2014; Gallina *et al.*, 2020; O'Neill *et al.*, 2022). Physical vulnerability focuses on the potential of a system to suffer physical damage (e.g., infrastructure damage) (Cremen, Galasso and McCloskey, 2022). Social vulnerability broadly considers societal damage; it includes physical vulnerability but also societal aspects (e.g., fatalities, hospitalizations, business interruption, economic losses) (Cutter, Boruff and Shirley, 2003; Oppenheimer *et al.*, 2014). Ecological vulnerability shifts its focus from societal to ecosystem damage (e.g., environmental resources damage, biodiversity loss) (Torresan *et al.*, 2016; Zebisch *et al.*, 2022). It is well known that vulnerability exhibits variations in time, not only as a response to the changes in hazard and exposure, but as the expression of societal evolution of the systems (Oppenheimer *et al.*, 2014). While the incorporation of adaptive processes makes systems less vulnerable, on the other hand, vulnerability can rise immediately after a hazard due to the suffered damage. In the context of multi-hazards, when more than one hazard hits the same location in a short time interval, it is extremely important to account for **vulnerability dynamics** (Ward *et al.*, 2022).

D. Responses: Incorporating responses into CRA frameworks

A number of studies have explored how **adaptation responses** can affect climate risk at local, national and international level including the socio-economic dimension in the risk assessment framework (Oppenheimer *et al.*, 2014; Dawson *et al.*, 2018; Warren *et al.*, 2018; Simpson *et al.*, 2021). For example, the study of Park and Vedlitz (2013) found that an individual's risk status and associated responses to climate hazards is determined by their **access to objective risk information and social connections**. Their findings indicate that individuals with higher access to information on climate risks and stronger social ties significantly influence proactive responses to climate hazards, while exposure to risk sources does not play a significant role in influencing climate behaviour. In addition, the authors indicate that political views or religious beliefs may condition the relationship between climate risks and responses by hindering individuals from obtaining accurate climate risk information or connecting with others with different concerns or information.

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Regarding the influence of **adaptation responses**, Jurgilevich *et al.* (2017) identified various studies that integrated the simulation and evaluation of adaptation measures and adaptation scenarios (business-as-usual, opportunistic adaptation, active adaptation) to gain understanding of risk-increasing factors. Adger *et al.* (2018) reviewed the practice of climate change risk assessment with focus on the adaptation policy development to manage climate-related risks. The authors highlight the influence of non-rational decision-making on risk factors due to the use of heuristics, which can introduce biases in risk perception (e.g., loss aversion, cognitive myopia and preference for maintaining the status quo). They also argue that these perceptual issues can lead to paradoxes in adaptation, such as varying preferences for adaptive responses and overreactions to perceived risks (*i.e., social amplification of risks)*, as well as the reinforcement of maladaptive responses.

Maladaptation, resulting from poorly planned and mismanaged adaptation strategies, generates undesired adverse consequences in both short- and long-term, and sometimes irreversibly so. Challinor *et al.* (2018) assessed the potential indirect effects of responses on risk leading to maladaptation. They provided the example of bringing more land into agriculture, which may reduce vulnerability in the short term but increase long-term climate risk through producing more greenhouse gas emissions. Similar results were described in Terzi *et al.* (2018), stating that misleading multi-risk assessments can result in the implementation of maladaptation practices. O'Neill *et al.* (2022) discussed current and future adaptation responses (i.e., institutional, behavioral/cultural, nature-based) including limits to adaptation and maladaptation. In order to reduce such issues, Torresan *et al*. (2016) proposed a framework, DESYCO, that provides decision makers with a set of adaptation measures to evaluate their ability to reduce risks. The framework allows decision makers to compare different options and select responses suited to their risk tolerance and adaptation priorities within the process of assessing climate risks at a regional level. By acknowledging that climate responses can alter risk levels, maladaptation is an issue to be considered from the very onset in the CRA process, it remains to be re-evaluated and tackled in the planning and implementation of adaptation measures.

In the context of **interactions and cascading effects within a multi-hazard framework**, Terzi *et al.* (2019) explore how adaptation responses generate cascading effects on other anthropogenic processes by considering their high interdependency. Simpson *et al.* (2021) proposed a new framework of risk, accounting not only for multi-drivers of risk and climate change, but also for the role of mitigation and adaptation responses in the risk condition. Additionally, Terzi *et al*. (2019) evaluated the effectiveness and applicability of adaptation options and strategies in addressing multiple risks in mountain regions, considering, among others, cross-sectoral interactions and cascading effects.

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All these complexities underscore the significant value of systematically collecting and interpreting a range of responses in climate risk assessment procedures. Doing so enables a better understanding of residual risks, risk tolerance, and societal perception of risk, that ultimately helps to develop more aligned policy interventions (Adger, Brown and Surminski, 2018).

E. Impacts: assessing the consequences of climate risks

When risks manifest, they become impacts. According to the AR6 Working Group II (IPCC, 2022a) significant impacts of climate change can already be observed for ecosystems and biodiversity as well as for human systems (water scarcity, food security, health and wellbeing, migration, cities, economic sectors, settlements and infrastructure).

Impacts of climate change are manifold and cross administrative, geographical, sectoral, governance and other types of boundaries (Hochrainer-Stigler *et al.*, 2023), which makes it important to include impacts in the economic evaluation of risks due to **low- and high-impact events** (Kaspersen and Halsnæs, 2017) together with probabilities. However, due to the large uncertainties involved, also non-probabilistic methods have been increasingly used in risk assessments – most prominently storyline approaches and counterfactual analysis of hotspot areas (Shepherd *et al.*, 2018).

Coleman, Esmalian and Mostafavi (2020) present an approach that builds on equity principles by accounting for sociodemographic characteristics contributing to **risk disparity**, recognising that the impacts of disruptions are disproportionately distributed in the social subpopulations. The authors assessed the risk disparity in terms of losses on well-being using two indicators: exposure (duration of the disruption) and zone of tolerance (people's ability to withstand disruptions), demonstrating that impacts are amplified in certain groups when lower tolerance and longer exposure are combined.

In the reviewed literature, mainly direct and some indirect impacts have been addressed (Oppenheimer *et al.*, 2014; Challinor *et al.*, 2018; Aznar-Siguan and Bresch, 2019; Zebisch *et al.*, 2022). While **direct impacts** are the biophysical effects of hazards on human systems such as infrastructure, assets or people, **indirect impacts** are considered effects of the direct impacts on socio-economic systems (affecting business or parts of the economic system, reliability of service provision or livelihoods) (Conway *et al.*, 2019; Cremen, Galasso and McCloskey, 2022; Rising *et al.*, 2022). Further, indirect impacts also affect human health and wellbeing (Lung *et al.*, 2013; Menk *et al.*, 2022), where it is important to not only reflect on mortality rates but also to go beyond including climate change impacts on morbidity (by affecting health or diseases), which is often overlooked (Lissner *et al.*, 2012).

According to Menk *et al.* (2022) direct and indirect impacts show a temporal character due to their time-shifted nature. Biophysical (i.e., primary) impacts eventually lead to subsequent, potentially

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human-centered risks, thus stressing the “secondary” aspect of indirect impacts (Conway *et al.*, 2019). However, impacts are not only categorizable temporally, but also cross-sectorally and spatially (Brown and Berry, 2022).

Indirect impacts can be seen through a lens of cascading or compound effects, with feedbacks and interconnections, and from a local to global dimension (Lam and Lassa, 2017; Dawson *et al.*, 2018; Brown and Berry, 2022). Further, just like for multi-risk, if multi-impacts are considered, another layer of complexity is added (Gallina *et al.*, 2020) as “multiple stressors” lead to “multiple endpoints” (Ronco *et al.*, 2017). Especially multi-impact events hold the potential to build political momentum, as further impacts are being triggered or exposure and vulnerability are shifted through e.g. population displacement (Challinor *et al.*, 2018).

3.1.3. Challenges & limitations of existing CRA frameworks

A. The complexity of climate-related risks

Climate-related risks are inherently complex and multifaceted, with various components and interactions that are not yet fully understood, especially when there is insufficient knowledge of the system of analysis (Menk, Terzi, *et al.*, 2022). While there are existing frameworks to provide a comprehensive understanding of climate change risks, these frameworks have several limitations and challenges that need to be addressed.

Dynamic feedback between hazard, exposure, and vulnerability is not well-comprehended, which makes it challenging to predict occurrence and progression of risk events (Ward *et al.*, 2022). Furthermore, low understanding of physical risks, their economic implications, and the nonlinearity of social feedback, obstructs the analysis of indirect risks and less-known causal risk pathways (Challinor *et al.*, 2018; Cremen, Galasso and McCloskey, 2022; Rising *et al.*, 2022). Additionally, CRAs struggle with the increasing complexity when assessing climate change effects on multiple sectors and the risk interconnectedness (Menk, Terzi, *et al.*, 2022), especially in distinguishing cause-effect relations from the multiple interacting factors, the natural variability, and threshold values (Brown and Berry, 2022). This lack of understanding makes it difficult to assess the interactions between multiple risks and their effects on the system components (Terzi *et al.*, 2019). Hence, there is often a tendency to compartmentalize individual risks for analysis and action, overlooking the interactions and interdependencies between risks (Brown and Berry, 2022).

As a result of such compartmentalization, views of future risks can be oversimplified while forgetting relevant considerations like emerging risks, adaptation limits, or adaptation opportunities, which may undermine the reliability and usability of CRA results among stakeholders. **Risk compartmentalization** is manifested in different ways:

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- By focusing on specific hazards ignoring other risks that may have serious consequences (Cremen, Galasso and McCloskey, 2022).
- By only considering the hazard variability as climate changes omitting variations in exposure and vulnerability over time (Jurgilevich *et al.*, 2017; Brown and Berry, 2022).
- By focusing on assessing multi-risk of various hazards individually under current conditions or specific scenarios rather than their interactions and feedback over time (Ward *et al.*, 2022).
- By leaving out relevant aspects for understanding the risks and impacts such as the adaptive capacity (of both nature and humans) or key parameters that describe the system's resilience and stability under different future climates and socio-economic pathways (Brown and Berry, 2022).
- By focusing on specific subsets of systems, such as particular sectors or communities, without considering important linkages in risk transmission (e.g., via supply chains) (Challinor *et al.*, 2018).

Particularly, compounding events or cascading effects, are often treated separately through different methods resulting in a fragmented understanding of the risk (Ward *et al.*, 2022). For instance, many risks are interconnected and can have cascading effects across different sectors and regions. However, when the multiple spatial and temporal scales involved in these risks are not considered in the assessment, it can result in misleading information about the wide range of disparate risks (Brown and Berry, 2022).

Despite the availability of various CRA methodologies, making the risk concept more actionable is still a challenge. For example, CRAs face methodological limitations like translating biophysical risks into financial or economic risks (Reisinger *et al.*, 2020; Rising *et al.*, 2022) or determining the variability of risk perceptions across different spaces, times, sectors, and cultural associations (Brown and Berry, 2022). Also, CRAs have complications in visualizing the many risk features, such as cause-effect relationships, feedback loops, spatial and temporal dynamics, and cross-component relations. That is why communicating and presenting multi-risk assessments can be as challenging as assessing them (Terzi *et al.*, 2019; Menk, Terzi, *et al.*, 2022).

- *Addressing the challenge of complexity*

How has the issue of **complexity** been dealt with in recent CRA literature? Zscheischler *et al.* (2018) highlight the need for collaboration between climate scientists, engineers, social scientists, impact modelers, and decision-makers to comprehend complex events. They emphasize considering multiple drivers, such as urbanization, infrastructure, and anthropogenic emissions, and how they interact with compound events to shape risk. Similarly, Simpson *et al.* (2021) propose a framework that recognizes the increasing complexity of climate change risks by focusing on the interactions among various risk drivers and encompassing both potential impacts due to climate change and

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responses to it. The authors argue that adoption of such thinking can encourage to identify between physical and socio-economic drivers of risk beyond the sectoral and regional boundaries.

Regarding the **incorporation of risk dynamics** into CRA, Jurgilevich *et al.* (2017) discuss the importance of considering changes over time on exposure and vulnerability as well as the integration of biophysical and socio-economic aspects for effectively address current and future challenges. In a recent study, Cremen, Galasso, and McCloskey (2023) also embrace risk dynamics by focusing on modeling and quantifying the individual components that shape tomorrow's risks, such as future natural hazards affected by climate change, changing exposure patterns (e.g., population, land use, built environment), and the evolving vulnerabilities of global infrastructure.

Moreover, advancements in **multi-risk assessment methodologies** and models enable better analyses of climate-related risks by considering the interrelationships between hazards. Through a comparative analysis, Terzi *et al.* (2019) examine models' effectiveness in representing the spatial and temporal dynamics, managing uncertainties, facilitating cross-sectoral assessments, integrating adaptation measures, and handling the required data and complexity. This analysis indicates that System Dynamic and Hybrid models exhibit high potential as effective tools for multi-risk assessment and climate change adaptation (Terzi *et al.*, 2019). In addition, (Tilloy *et al.*, 2019) identify different types of hazard interrelations (i.e., triggering, change condition, compound, independence and mutually exclusive) and 19 modelling methods (stochastic, empirical, and mechanistic) to quantify them, while providing insights into how to account for cascading and compounding hazards. Furthermore, Gallina *et al.* (2020) present a multi-risk approach that combines multiple climate-related hazards, exposure, and vulnerability factors, using GIS and statistics to identify high-priority multi-hazard and multi-vulnerability areas in different spatial and temporal scales. More recently, Hochrainer-Stigler *et al.* (2023) propose a six-step framework for analyzing and managing risk across various levels, ranging from single to multi and systemic risks. This integrated approach aims to enhance real-world applications of multi-risk assessment.

Accounting for **transboundary and cross-sectoral risks and impacts** is also crucial in adopting a more systemic perspective in CRA. Under that lens, Challinor *et al.* (2018) propose a new approach that distinguishes the roles of climate and socio-economic systems in risk transmission, along with reviewing different modeling, qualitative, and systems-based methods for assessing transmitted risks and risk amplification. Also, Harris *et al.* (2022) introduce a protocol that helps incorporate analysis of transboundary risks by leveraging principles for managing complex risks and frameworks for assessing risk ownership across different scales. Carter *et al.* (2021) developed a conceptual framework for cross-border impacts and emerging risks following the logic of *initial impacts* and *downstream consequences (recipient risk)* including impact and response dynamics. Also, the event-based storyline approach enables to follow a chain of events with possibly transboundary and cross-

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sectoral impacts (van den Hurk *et al.*, 2023). In the context of policy-making and adaptation investment, Dawson *et al.* (2018) develop a systems approach that evaluates climate risks and necessary adaptation actions across all infrastructure sectors. By considering the interconnectedness of sectors, authors attempt to provide a comprehensive understanding of climate risks.

B. The intrinsic uncertainty of CRAs

CRAs have many uncertainties involved in each component of the assessment, which poses a significant challenge for predicting future risks precisely (Cremen, Galasso and McCloskey, 2022). Modelling future changes of and impacts' variability on each component is difficult; that is why these aspects are often neglected (Menk, Terzi, *et al.*, 2022). For example, projecting future changes in vulnerability is highly uncertain, considering that it depends on socio-economic aspects such as education, wealth, health, and how they interact (Jurgilevich *et al.*, 2017). Table 1 summarizes some other sources of uncertainty involved in the CRA process.

While efforts to address these issues are growing in the literature, essential information for more precise estimations of risks and impacts in future scenarios remains insufficient. Some other aspects in which climate science needs to set a research agenda to reduce uncertainty layers are: the understanding of risk dynamics, information about future exposure and vulnerability, high-quality data on extreme events, and "un-hiding" risk factors across socio-ecological systems (Jurgilevich *et al.*, 2017; Melo-Aguilar, Agulles and Jordà, 2022; Rising *et al.*, 2022; Zebisch *et al.*, 2022).

Table 1. Sources of uncertainty.

Source of uncertainty	Source
Imperfect knowledge: only uncertainty that can be expressed with numbers is considered neglecting those non-quantifiable.	(van der Sluijs, 2012)
Unequivocalness: relying on consensus as the only proxy for truth, leaving other relevant issues without consensus underexposed.	(van der Sluijs, 2012)
Irreducible ignorance: accepting that uncertainty and dissent are permanent, and science cannot provide an answer.	(van der Sluijs, 2012)
Structural uncertainty: incomplete understanding of processes and components in climate, impact, and economic models.	(Kaspersen and Halsnæs, 2017)
The noise of natural fluctuations: distinguishing climate change impacts in specific locations from natural fluctuations.	(Kaspersen and Halsnæs, 2017)
Downscaling extreme events models: estimating the probability of low-frequency, high-intensity events in specific locations by downscaling data from global models.	(Kaspersen and Halsnæs, 2017)

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Source of uncertainty	Source
Individualization of impacts: estimating impacts within varied risk perceptions and risk-aversion attitudes across the society.	(Kaspersen and Halsnæs, 2017)
Cross-sectoral sensitivities: changes in sectoral sensitivities in a changing climate.	(Challinor *et al.*, 2018)
Physical teleconnections: changing physical teleconnections that can affect sectors and regions differently.	(Challinor *et al.*, 2018)
Unexpected changes in systems: unprecedented socio-economic and environmental changes and their interactions with climate change effects.	(Conway *et al.*, 2019)
Incomplete climate impact pathways: insufficient characterization of climate change effects in the human and natural systems, including direct and indirect impact pathways, webs of interconnections, and propagation mechanisms at various temporal and spatial scales.	(Conway *et al.*, 2019; Melo-Aguilar, Agulles and Jordà, 2022)
Masking of climate change effects: overlapping climate change effects (exempting extreme events) with other dynamics, like urban development or demographic changes.	(Conway *et al.*, 2019)
Risk aggregation: assumptions made upon integrating information from different scales and sources to assess overall risks and priorities.	(Harrington, Schleussner and Otto, 2021)
Relative importance of each input factor: quantifying the relative importance of every risk factor in different exposed systems and in an evolving landscape of multiple risks.	(Harrington, Schleussner and Otto, 2021; Melo-Aguilar, Agulles and Jordà, 2022)
Plausibility of future scenarios: intrinsic uncertainty of climate models in predicting multiple future scenarios and projections, which are also dependent on unknown factors like population changes and changes in global governance.	(Harrington, Schleussner and Otto, 2021)
Evolving adaptive capacity: modelling how quickly and effectively people and systems will adapt to the changing climate.	(Harrington, Schleussner and Otto, 2021)
Spatial patterns of hazards: representing the spatial distribution of climate hazards and their impacts against local risk thresholds for different types of hazards.	(Harrington, Schleussner and Otto, 2021; Rising *et al.*, 2022)
Temporal variations: variability of climate impacts over time, including feedback loops and interacting risks.	(Rising *et al.*, 2022)
Deep uncertainty: unidentified or yet unknown risks, including "black swan" events.	(Rising *et al.*, 2022)
Imprecise assessment models: outdated assessment models, or imprecise estimation of the extent of impacts and their spatiotemporal probability and frequency.	(Rising *et al.*, 2022)

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Source of uncertainty	Source
Uncertain datasets: intrinsic uncertainty in input data and inconsistency between datasets used for climate modelling.	(Melo-Aguilar, Agulles and Jordà, 2022)

Yet, more adequate methods for assessing uncertainty are missing, as well as means to improve sensitivity and confidence levels in CRAs. One example of this need can be reflected in the use of SSP (Shared Socio-economic Pathways) scenarios, in which uncertainties of each computational model and projections propagate to the final risk estimation (Melo-Aguilar, Agulles and Jordà, 2022).

The points described above show that CRAs are not only about predicting impacts or risk probabilities; they are also about gaining knowledge to reduce epistemic uncertainties and progress towards adaptation (Adger, Brown and Surminski, 2018; Sutton, 2019). In the meantime, uncertainties in CRA remain prevalent (van der Sluijs, 2012), and CRAs can only offer a limited idea of how the future will be.

- *Addressing the challenge of dealing with uncertainty*

Several authors have attempted to reduce CRA uncertainty from different angles. Kaspersen & Halsnæs (2017) found that climate and socio-economic assumptions can significantly impact the outcomes of the CRA. By integrating uncertainty from all factors of the risk propellor (hazard, exposure, and vulnerability) according to IPCC AR5 (IPCC, 2014), simulated scenarios and assessed risks can be provided with confidence levels (Melo-Aguilar *et al.*, 2022). This integrated approach of including vulnerability and exposure can also be found in Harrington, Schleussner and Otto (2021), where uncertainties get assessed within the IPCC “Reasons for Concern” framework.

According to (Rising *et al.*, 2022) uncertainties in CRAs emerge from “missing risks”. These refer to i) impact models, which are out of date, ii) spatial and temporal extremes, iii) feedback risks and *black swan* events (high impact – low probability), iv) deep uncertainty and v) unidentified risks. As the reason for uncertainty is thus known, the solution seems more evident: “better models” with more detailed scenarios and input (multi-sector, multi-model projections) can provide solutions for remaining risks. However, there is a fundamental limit to how well models will be able to cover the complexity of risks. In turn, a more intensive, interdisciplinary collaboration between natural, engineering and social sciences can reduce uncertainty by including broader perspectives. Due to the time delay between the biophysical risk and its socio-economic feedback, uncertainty will persist.

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Another approach has been described by Melo-Aguilar, Agulles and Jordà (2022). According to their probabilistic impact chain approach, uncertainty needs to be addressed and included in every component of a CRA. By selecting, quantifying and weighting input indicators for the impact chain approach, uncertainties can be dealt with.

However, uncertainty remains a big issue for CRAs regardless of approaches taken. Van der Sluijs (2012) discusses a post-normative perspective of (deep) uncertainty with two possible directions: one where uncertainty is considered to be a missing piece of the current knowledge status or, antagonistically, **accepting uncertainty** and including it into CRAs when possible. With the paradigm of “uncertainty reduction” potentially reaching its limits, "making uncertainty manageable" is a promising path to be pursued by, for example, following an event-based storyline approach (e.g. Sillmann *et al.*, 2021), exploring adaptation tipping points (e.g. Kwadijk *et al.*, 2010) or scouting “solution spaces” for adaptation options (e.g. Haasnoot *et al.*, 2020).

C. Adding probability to CRAs

Probabilistic Risk Assessment (PRA) has been proposed and implemented to cope with the different sources of uncertainty linked to natural hazard impact. The main goal of PRA is to assess impact in terms of likelihood and not by providing a deterministic value. In the case of flooding, this can be done by providing a probabilistic impact based on an ensemble of water level values resulting from different scenarios of model input and levee breaches along a river (Mazzoleni *et al.*, 2014). The main assumption of PRA methods is that climate conditions are stationary, meaning that the statistical properties of the climate system remain constant over time (Cheng and AghaKouchak, 2014). As discussed above, this assumption can create misleading results as it has been shown that the non-stationarity nature of climate change will lead to significant shifts in the frequency, intensity, and spatial distribution of extreme weather events (IPCC, 2012). Climate processes are affected by non-linear behavior, multi-scale variability, and can be influenced by both natural and anthropogenic factors (Hurrell *et al.*, 2009), leading to a significant challenge for PRA in a non-stationary climate.

One main challenge of PRA methods is that they often use historical records of weather events to estimate the probabilities of future events (Milly *et al.*, 2008). However, in case of a non-stationary climate, the statistical properties of past events cannot be used to represent the future conditions. This can lead to substantial underestimation or overestimation of climate risk, leading to inadequate adaptations and mitigation strategies (Kreibich *et al.*, 2017). Another challenge lies in the varying future correlation between climate and e.g. hydrological variables such as flood peak and volume, which could potentially affect the future joint probability distribution (Serinaldi and Kilsby, 2015). As a result, these changes could significantly alter future risk assessment, as the likelihood of extreme events can significantly affect the overall risk. Accounting for these evolving dependencies is crucial for accurate risk assessment. Model uncertainty is another challenge that can affect PRA due

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to the uncertainty propagation from input, initial conditions, model structure, and model calibration, up to the risk assessment (Harrington, Schleussner and Otto, 2021). These uncertainties also include the unpredictability of climate processes (Hawkins and Sutton, 2009).

In order to address such challenges, a number of research advances are needed. First, new approaches able to account for the time-varying nature of extreme weather events to be developed (Salvadori *et al.*, 2016). Second, a better quantification of the modelling chain uncertainty is required by, for example, developing ensemble-based approaches accounting for a number of climate model projections (Tebaldi and Knutti, 2007). Third, PRA approaches should be adapted to include the effect of climate adaptation strategies in changing social vulnerability and exposure, thus consecutively reducing risk (Kreibich *et al.*, 2017). In this way, PRA would allow for a more accurate risk assessment of future risks and inform stakeholders and decision-makers better. Finally, an interdisciplinary collaboration among scientists from different research fields and stakeholders is needed to address the challenges posed by non-stationary future climates.

D. CRA approaches and choices

The urgency of addressing climate change has brought forth diverse methods to assess climate risk, ranging from **top-down global models to bottom-up localized assessments**. However, this variety of approaches has created a choice problem for decision-makers and relevant stakeholders, especially at sub-national levels. Besides that, the strengths, limitations and inherent trade-offs of CRA approaches also play a significant role in the selection process. Below, the limitations and drawbacks of each CRA approach are further detailed, highlighting the challenge of opting for one over the other.

- *Top-down approaches and their shortfalls in capturing the complexity of climate risks*

In general, top-down approaches struggle to capture the complexity of risk processes, including the many different factors and risks interacting in complicated ways (Berkhout *et al.*, 2013; Aznar-Siguan and Bresch, 2019; Terzi *et al.*, 2019; Brown and Berry, 2022; Kropf *et al.*, 2022). In other words, many risk models do not integrate how risk components (nor responses) are interconnected or how risks can have diverse effects (*i.e.,* aggregation, compounding, and cascading (Simpson *et al.*, 2021)). For example, Bayesian Belief Networks[7] models fail to capture feedback loops from the response variable back to the drivers, making it difficult to understand how different factors interact in complex ways (Onyango *et al.*, 2016). Therefore, top-down approaches give limited notions of how risks affect people's lives, how people's behavior can affect the risks they face, or how people may respond to them (Terzi *et al.*, 2019).

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[7] A widely employed statistical model, particularly in addressing uncertainty, that represents variable relationships using probabilities and is recognized for its ability to describe dependencies and independencies between variables, with applications in risk assessment, decision support, and environmental modelling (Landuyt *et al.*, 2013).

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Typically, models have “blind spots” in their analysis because they may not have enough historical data to predict future risks reliably (Challinor *et al.*, 2018). Likewise, when identifying economic and social impacts, many top-down techniques are not designed to analyze the climatic effects on assets with additional non-monetary values, such as cultural or historical places (Menk, Terzi, *et al.*, 2022). Similar issues happen when assessing risks in ecosystems and biodiversity, given that climate risk models often rely on primary climate data rather than bioclimatic data (Brown and Berry, 2022). This limitation can hide the actual ecological, economic and societal costs of climate impacts.

Besides that, there are two other caveats in top-down CRAs. The first is related to the ambiguity in defining "referenced conditions" (Brown and Berry, 2022), which are those conditions to use as a baseline for comparison when evaluating future climate risks. Since different models may use different baselines depending on their goals and assumptions, the evaluation and comparison between models becomes problematic. This leads to the second caveat, the “shifting baselines” syndrome (Brown and Berry, 2022). In top-down CRAs, different baselines can estimate changes and impacts on ecosystems and human well-being differently, making it difficult to predict future risks and interpret the results of climate risk models appropriately.

There are other top-down techniques for CRA besides conventional climate risk models. One of them is using **composite indicators**, which have been widely used in assessing climate risks at a high level. However, one of its main limitations is the high subjectivity implicit in the normalization of values as well as the choice and weighting of the indicators (Zebisch *et al.*, 2021). Normalization and weighting processes require subjective judgments, such as choosing minimum and maximum values for each indicator and determining their importance and relative weight, which can introduce biases into the assessment.

Most recently, **machine learning – an artificial intelligence (AI) technique**—has been increasingly used in CRA. Yet, its use has limitations, particularly in terms of interpretability. Predictions made by Machine Learning algorithms are through a "black box", meaning that is difficult or impossible to understand how the algorithm is learning about the risk as well as identify and correct any biases or errors in it (Zennaro *et al.*, 2021). Consequently, the accuracy and reliability of its predictions can be questioned due to their lack of transparency.

Apart from that, the technical nature of top-down CRAs also limits their **communication**. Top-down approaches for CRA can provide valuable insights into potential future risks, but their results are not always directly useful for decision-making and adaptation planning in the present (Conway *et al.*, 2019). It is recurrent that climate model results need to be translated and contextualized to make them more accessible, relevant and actionable, as well as to suit the specific needs of different stakeholders, such as government agencies, communities, and individuals (Conway *et al.*, 2019;

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Melo-Aguilar, Agulles and Jordà, 2022). However, doing so can carry other complications. For instance, translating CRAs for non-expert audiences inevitably leads to reductionism and loss of information. In the same way, contextualizing and matching results with stakeholders' needs can have inadvertent consequences such as overestimating the model's reliability, misalignment of priorities, or political bias and misrepresentation of data.

Lastly, top-down approaches can provide useful high-level information about climate risks, but they may not capture the specific risks at a local level (Lam and Lassa, 2017; Conway *et al.*, 2019; Sutton, 2019). Usually, climate risk models do not fully represent risk processes' spatial and temporal dynamics, limiting the understanding of how risks affect different parts of a region over time (Conway *et al.*, 2019; Terzi *et al.*, 2019; Rising *et al.*, 2022). For instance, they may provide broad statements about how different sectors, such as agriculture or water resources, will be affected by climate change without giving the specificities and enough detail to understand the risks in each sector. Thus, it is important to explore bottom-up approaches for a more context-specific understanding of climate risks.

- *The practical pitfalls of bottom-up approaches*

While **bottom-up approaches** can effectively generate locally relevant information for identifying vulnerabilities and assessing climate risks, they have several limitations, methodological rather than conceptual.

Just like top-down approaches, the bottom-up ones also have difficulties communicating complex interconnections between different risks and systems in an understandable way for a non-expert audience (Terzi *et al.*, 2019). Indeed, **participation and active engagement** of various stakeholders are among the main concerns in CRA bottom-up approaches. That is why bottom-up approaches frequently simplify risk complexity – or even neglect it – at the cost of more extensive participation (Menk, Terzi, *et al.*, 2022).

Overall, bottom-up approaches use tools and methodologies that heavily rely on participant data (Cavan and Kingston, 2012; Melo-Aguilar, Agulles and Jordà, 2022), which can vary widely between different groups of participants (Menk, Terzi, *et al.*, 2022) and, although relevant, is often **subjective and lacks precision and spatial precision distinction** (Zebisch *et al.*, 2021). Even in some cases, like in climate impact chains methodology, expert judgement, and climate risk narratives, it may result in imbalanced stakeholder involvement, with assessments developed from only a few groups' perspectives and underrepresenting marginalized communities (Zebisch *et al.*, 2021; Menk, Terzi, *et al.*, 2022).

Additionally, some tools or methodologies require a certain level of expertise from the participants which can lead to a lack of representation of certain stakeholder groups. For example, Cavan and

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Kingston (2012) mentioned not all participants have the necessary technical skills to use or understand a GIS tool to map and visualize risks in a particular area, limiting the participants' ability to contribute to the assessment process.

Further limitations in bottom-up approaches are **low replicability and consistency of results** and collected data (Zebisch *et al.*, 2021), lack the objective rigor to avoid biases and subjectivity (Melo-Aguilar, Agulles and Jordà, 2022), disregard of risk transmission mechanisms and interconnectedness across scales (Challinor *et al.*, 2018; Conway *et al.*, 2019), low scalability and generalization of results (Conway *et al.*, 2019), and low applicability at a large scale (e.g., regional, national, transnational) considering it would demand complicated logistics, substantial amount of resources, and a high level of expertise to standardize methods and data (Zebisch *et al.*, 2021).

Finally, bottom-up approaches focus on representing conditions **at a specific timeframe** to build upon that the assessment of risks without fully explaining how those conditions change over time or how transitions can occur as risks evolve and interact within system components (Menk, Terzi, *et al.*, 2022). By developing participatory climate scenarios which concentrate on how future climate conditions will shape socio-economic dynamics without considering vice-versa influences of socio-economic dynamics on climate risk factors (Conway *et al.*, 2019) can result in an incomplete understanding of the complex interplay between climate and socio-economic systems and may lead to a failure to address the root causes of climate risk adequately. This issue has been addressed as part of the event-based storyline approach by comparing a baseline reference storyline to one or several so called "counterfactuals", thus accounting for different "climatological or socio-economic conditions" (van den Hurk *et al.*, 2023, p. 5).

Why integrated approaches are (still) not enough

While combining both top-down and bottom-up approaches (i.e., ***hybrid models***) can enhance the comprehensiveness and accuracy of CRAs, data gathered from each approach tends to be different, and harmonizing it can be problematic (Conway *et al.*, 2019). Combining data can also bring verification issues to the CRA, considering that some aspects, such as exposure and vulnerability, are sometimes assessed using indirect or subjective methods (Melo-Aguilar, Agulles and Jordà, 2022).

In integrated approaches, such as Multi-Risk Assessments, the absolute risk value masks the actual size of individual hazards and the severity of their impacts (Lung *et al.*, 2013). Irrespective of accounting for many aspects, such as human responses, bioclimatic processes and socio-economic dynamics, integrated assessments are still limited in analyzing which variables or processes are more influential in driving, transmitting or amplifying risks (Onyango *et al.*, 2016), as well as the challenging choices that politicians encounter when they need to address the concerns of relevant stakeholders (Peng *et al.*, 2021).

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- *The tools' choice problem*

Along with the emergence and combination of various approaches for assessing climate risks, many methodologies have fraught the CRA field creating a complex choice problem: despite the multitude of tools available, choosing the most suitable one can be daunting. For example, different models can lead to significant differences in hazard and vulnerability levels, even when using the same emission scenario (Lissner *et al.*, 2012; Conway *et al.*, 2019), which, however, needs to be considered within uncertainty management.

With many qualitative and quantitative methods scattered across various scientific communities, disciplines, and publications, it can be quite challenging to identify the most appropriate tool for a specific context (Ward *et al.*, 2022). On the one hand, quantitative methods are data-driven and can be highly technical requiring significant expertise that involve accessing, handling, and analyzing climate data, future scenarios, impact models, as well as controlling the quality of socio-economic data (Zebisch *et al.*, 2021). For instance, multi-risk approaches often demand specialized knowledge and technical capacity, which are not always readily available (Conway *et al.*, 2019; Gallina *et al.*, 2020), while those assessments with less dependency on quantitative analysis, such as impact chains, still demand a data-rich environment that supports decisions on normalization, weighting, and aggregation steps (Zebisch *et al.*, 2022).

On the other hand, the challenges of bottom-up tools are related to ensuring consistency and representativeness of information (Conway *et al.*, 2019), which makes these tools time and resource intensive due to the regular involvement of experts and stakeholders throughout all research phases as well as a need to standardize assumptions to allow comparison across CRA (Menk, Terzi, *et al.*, 2022).

When it comes to hybrid models, challenges are related to the compatibility of different models and the harmonization of disparate information, especially when models to be integrated are built upon different assumptions or use various data sources and scales, which require careful consideration to ensure accurate and reliable results (Conway *et al.*, 2019; Terzi *et al.*, 2019).

Proponents and designers of tools, methods and models often focus on presenting the advantages and strengths of their innovations and developments, without emphasizing specific limitations, general constraints or requirements for a successful implementation, which complicates the technique selection process. Such overview of tools and methods is still missing, and to facilitate the methodological progress of CRA, tools' proponents (researchers and practitioners) should not only be more transparent regarding cons and pros of the tool, but also consider the needs and capacity of the end-users (Berkhout *et al.*, 2013).

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E. The data struggle

One of the major struggles faced by CRAs is the availability and access to reliable data for quantitative analysis. According to Menk, Terzi, *et al.* (2022), data scarcity and inconsistency due to heterogeneous spatial scales or resolution may lead to discard important risk factors, affecting the accuracy of CRAs. Challinor *et al.* (2018) also mention that the lack of data introduces high uncertainty in model-based frameworks and limit the description of risk transmission pathways across sectors and borders.

Limited access to exposure and vulnerability data, especially socio-economic data, is a significant bottleneck for projecting and assessing future risk dynamics (Jurgilevich *et al.*, 2017), as well as the lack of information of extreme weather events (Gallina *et al.*, 2020). This becomes more problematic when calibrating and validating models, given that climate change and socio-economic data are usually inconsistent (Lissner *et al.*, 2012; Zebisch *et al.*, 2021) and datasets featuring extreme events are strongly distorted (Zennaro *et al.*, 2021).

To compensate the deficit of high-resolution regional and local data, frequently global climate models are downscaled using a variety of methods aiming to have a higher resolution of local effects and more relevant projections of future climate changes at smaller scales (i.e., regions, states, cities). However, when downscaling is not applied properly, or when observational local input data (e.g., historical data) is not available, it may worsen the data problem by introducing additional sources of uncertainty and having dissatisfactory bias-correction to the local conditions which may produce inaccurate projections. For instance, while downscaled models help overcome the lack of consistent meteorological data by filling in the gaps in the time series, Zebisch *et al.* (2021) mentioned that limitations in climate model data usually relate to missing or inadequate adjustments to local conditions or incomplete climate datasets.

Additional challenges arise when data is needed to represent a system accurately. Normally, it requires collecting and working with a large amount of data, mainly related to qualitative aspects (Terzi *et al.*, 2019), to later translate and integrate it into models (Melo-Aguilar, Agulles and Jordà, 2022). This has to be done carefully, for example, when choosing the right indicators of vulnerability that can represent the actual conditions while being univocally comprehensible for policymakers and stakeholders (Parker *et al.*, 2019). In that sense, any inaccuracies may result in suboptimal risk assessments and, thus, misleading adaptation responses.

F. Barriers to influence decision-making

CRA provides essential information for decision-making, but decision-makers often face several challenges in translating these results into local action (Figure 5). To be policy-relevant and satisfactory for decision-makers, CRA requires an extensive evidence base with enough confidence levels

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and high independent consensus (Torresan *et al.*, 2016; Brown and Berry, 2022) and able to capture the unequal distribution of benefits and costs (“winners” and “losers”) of the changing climate (Peng *et al.*, 2021). This can be particularly problematic when power imbalance and conflicting interests exist, which may bias the assessment and the risk management decisions (Challinor *et al.*, 2018; Menk, Terzi, *et al.*, 2022).

NORMATIVE CHOICES

1. Determining an appropriate or acceptable level of risk and identifying who has the authority to define it.
2. Clarifying what would be considered sufficient measures to address the impacts of climate change.
3. Selecting the scenarios to be analyzed when assessing risks.
4. Making decisions about objectives and priorities, considering conflicting viewpoints and differing perspectives on what should be prioritized.
5. Evaluating performance against social, environmental, and economic objectives and determining how to weigh each objective based on local preferences.
6. Assessing future costs and benefits.
7. Addressing distributional and intergenerational issues related to the current costs and benefits of climate risks across various societal groups.

POLITICAL REALITIES

1. Communicating the necessity of revising and reevaluating strategies to the general public, while acknowledging the potential risk of it being perceived as a failure and impacting political capital and reputations.
2. Making decisions under conditions of high uncertainty, where various pressures and competing goals must be balanced.
3. Fostering local participation in assessing climate risks, and integrating diverse perspectives on risks.
4. Obtaining support from local communities and other stakeholders in the management of climate risks by facilitating public debate.
5. Avoiding the misuse of climate change as a wildcard in politics and decision-making.

COMMUNICATING THE SCIENCE

1. Interpreting carefully the highly-detailed and complex data derived from climate risk assessments.
2. Transparency regarding the usability and limitations of information is crucial, specifying which data can be utilized for specific decisions.
3. Building a shared understanding of risk and of the problem at hand among relevant stakeholders.
4. Recognizing the relevance of information for local decision-making, as well as the data and methods used.
5. Understanding the connection of CRAs to political processes, including the context of where, when and the timespan of the decision.
6. Acknowledging uncertainties in relation to various climate change scenarios.

Figure 5. Theoretical problems of data ‘salience’ and ‘translating’ information from risk analysis into normative policy action (Based on McDermott and Surminski, 2018)

McDermott and Surminski (2018) demonstrate that even with improved data accuracy and a wider range of theoretical approaches at their disposal, local decision-makers' actions are ultimately guided by the normative interpretation of this information. Utilizing risk assessments for decision-making involves making normative choices, such as defining "acceptable risk levels" and determining "adequate" protection levels, which involves broader consensus and stakeholder participation to secure decisions’ acceptability (McDermott and Surminski, 2018).

That leads to another challenge that relates to the interpretability of the CRA results, especially at higher levels of aggregation. Increasing volume of data is not enough to ensure better-informed decisions; it needs interpretation (McDermott and Surminski, 2018). In such cases, large-volume data products can become less helpful for adaptation activities, making it difficult to translate them into actionable information (Zebisch *et al.*, 2021).

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Ultimately, the most significant challenge in utilizing CRAs for decision-making is to provide useful and applicable results that stakeholders can use to develop adaptation measures (Gallina *et al.*, 2016). This may explain why there is still a mismatch between climate risks and adaptation responses (Brown and Berry, 2022), but above all, it highlights the need for better communication strategies that can provide understandable and functional information to the stakeholders.

3.1.4. Opportunities for the new generation of CRAs

A. *Trends and overlooked themes*

In the CRA field, there are notable trends shaping the latest developments. The IPCC has played a significant role in influencing the field by consolidating the most up-to-date knowledge. For instance, IPCC's Working Group II has embraced a dynamic view of risk to identify key risks across sectors and regions today and in the future in AR6 (O'Neill *et al.*, 2022). Table 2 summarizes trends driving conceptual and methodological advancements in the CRA field that were identified from the reviewed literature.

Table 2. Trends and innovations in CRA.

Trending issue	Innovation/Development	Source
Spatialization of risk	Identification and aggregation of multiple hazard types at the regional and local scale	(Gallina *et al.*, 2016)
	Use of Remote Sensing to identify and rank risk hotspots	(Lung *et al.*, 2013; Ronco *et al.*, 2017; Terzi *et al.*, 2019)
Participation	Integration of local perception of risks	(Terzi *et al.*, 2019)
	Wider engagement of local stakeholders to assess present day and future risks as well as hazards, exposure and vulnerability individually	(Challinor *et al.*, 2018; Warren *et al.*, 2018; Brown and Berry, 2022)
	Exploration of the influence of diverse and evolving societal values and norms in assessing and interpreting risk tolerance	(Brown and Berry, 2022)
	Integration of practitioners into the stakeholder consultation process	(Brown and Berry, 2022)
	New forms of engagement, such as Gamification and Serious Games, Interactive Scenario Building, Backcasting, Pathways Mapping	(Challinor *et al.*, 2018; Terzi *et al.*, 2019)
	Use of Machine Learning to assess multiple risks	(Challinor *et al.*, 2018; Zennaro *et al.*, 2021; Ruane *et al.*, 2022)

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Trending issue	Innovation/Development	Source
New Technologies and sophisticated techniques	Focus on Decision Tree, Random Decision Forest, and Artificial Neural Networks as ensemble predictive methods	(Zennaro *et al.*, 2021)
	Exploitation of Big Data analytics, Information and Communication Technologies (ICT), and network analysis to identify emergent patterns of social behavior and run several risk scenarios and cascading uncertainties in space and time	(Challinor *et al.*, 2018; Gallina *et al.*, 2020)
Integrated Assessment Models	Hybridization of probabilistic models to reduce uncertainty	(Shortridge and Zaitchik, 2018; Terzi *et al.*, 2019; Melo-Aguilar, Agulles and Jordà, 2022; Doss-Gollin and Keller, 2023)
	Ensembles mainly oriented to model flood and landslide risks	(Zennaro *et al.*, 2021)
	Combination of models associated to climate change impacts	(Challinor *et al.*, 2018; van den Hurk *et al.*, 2023)
Effect of adaptation responses	Integration of the influence of responses in the risk generation	(Gallina *et al.*, 2020; Simpson *et al.*, 2021)
	Prevention of maladaptation	(Gallina *et al.*, 2020; Arribas *et al.*, 2022)
Validation and calibration of information	Integration of results from top-down and bottom-up approaches for better decision-making (e.g., projections complemented with narrative-based descriptions	(Dessai *et al.*, 2018; Conway *et al.*, 2019)
	Use of multi-disciplinary and heterogenous sources of information and scenarios (climate, environmental, socio-economic)	(Torresan *et al.*, 2016)
Uncertainty handling	Quantification and integration of all types of uncertainties (e.g., climate model, socio-economic uncertainty, and vulnerability) into the final risk	(Harrington, Schleussner and Otto, 2021; Melo-Aguilar, Agulles and Jordà, 2022)
	Event-based storyline approach	(Shepherd *et al.*, 2018; Sillmann *et al.*, 2021; van den Hurk, Baldissera Pacchetti, *et al.*, 2023)
	Use of a probability density function that describes the uncertainty associated to each risk component.	(Melo-Aguilar, Agulles and Jordà, 2022)

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While some topics and areas are fostering conceptual and methodological advancements in CRA, others are overshadowed. For example, the hazard component has received more attention in risk assessment literature, while the need for interactions of vulnerability and exposure factors in the multi-risk issue has been neglected (Gallina *et al.*, 2016; Jurgilevich *et al.*, 2017; Terzi *et al.*, 2019; Menk, Terzi, *et al.*, 2022). This prevalence has also led to primarily associate climate risk uncertainties with statistical measures of the magnitude and frequency of the hazard, ignoring other important factors (Melo-Aguilar, Agulles and Jordà, 2022). Something similar happened in the analysis of risk dynamics, in which socio-economic aspects have been often overlooked, eclipsed by a stronger focus on biophysical dynamics (Jurgilevich *et al.*, 2017).

Such imbalances in the literature can also be noticed in the CRA approaches, with the current body of literature predominantly describing top-down applications, which highlights the need for more recognition of the bottom-up approaches (Conway *et al.*, 2019). Likewise, in the emerging field of Machine Learning, Zennaro *et al.* (2021) found that most CRA applications have focused on evaluating risks under current conditions, rather than future climate change scenarios or cascading and compounding risks.

Although there are notable trends and interesting innovations that can enhance the CRA effectiveness, certain aspects still require further attention and balance.

B. New Tools for CRA

The progress of climate risk understanding together with technological advancements has introduced new methodologies that enable not only more accurate CRAs, but also more user-friendly tools for supporting decision-making and adaptation planning.

In terms of practical tools, Torresan *et al.* (2016) proposed DESYCO, a user-friendly GIS-based decision support system tailored for local risk evaluation and management that utilizes a Regional Risk Assessment (RRA) methodology coupled with a Multi-Criteria Decision Analysis (MCDA) model. It integrates hazard, exposure, susceptibility, risk, and damage assessment, with climate scenarios, hydrological simulations, and non-climate vulnerability factors through intuitive interfaces that facilitate risk mapping and result communication. Additionally, Aznar-Siguan *et al.* (2019) introduced CLIMADA, an open-source software specifically designed for CRA, presented in a modular and collaborative design that allows scalable computation. By integrating hazard, exposure, and vulnerability data to assess risk and quantify socio-economic impact, the software supports multi-hazard calculations and employs an event-based probabilistic approach that maintains global consistency across various resolutions, making it suitable for both broad-scale and localized studies (Aznar-Siguan and Bresch, 2019). Indeed, open access platforms, such as the CLIMADA toolbox, can improve

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CRAs by increasing accessibility to data and foster knowledge exchange among users and stakeholders.

In terms of more accurate CRAs, Cremen, Galasso, and McCloskey (2023) provided an overview of efforts to model future climate hazards, exposure, vulnerability, and the metrics used to define future risks. Furthermore, Menk, Terzi, *et al.* (2022) focused on the Impact Chain methodology and similar approaches that consider the cause-effect dynamics governing risk, concluding that an impact web-like representations or risks would allow for a more comprehensive integration of cause-effect relationships.

In their study, Zennaro *et al.* (2021) conducted a comprehensive review of Machine Learning methods applied to CRA, revealing that are often combined in ensemble or hybrid approaches, leveraging remote sensing data to identify exposure and vulnerability targets, as well as detect environmental and structural features. Authors identified that among a wide array of algorithms, Decision-Tree, Random Forest, and Artificial Neural Network are the most commonly employed in CRAs, and argued that other technologies such as cloud computing and drones allow for the creation of more actionable and locally relevant information. This could be highly beneficial for improving CRAs given the often deficit of local data.

C. Stakeholders' engagement and integration of local knowledge

One of the most prominent discussions in CRA literature is the **involvement of local stakeholders** to allow better use of local information and promote eventual uptake by the stakeholders using the CRA in their decision-making process (Gallina *et al.*, 2016; Torresan *et al.*, 2016; Conway *et al.*, 2019; Peng *et al.*, 2021; Brown and Berry, 2022; Porter and Clark, 2023), thus overall leading to more practical use of CRA in adaptation planning (Gallina *et al.,* 2016; Porter & Clark, 2023) and better integration of the local context.

Arribas *et al.*, (2022) define participatory governance as one of four cross-cutting critical paths for the improvement of CRAs. The facilitation of participatory and inclusionary spaces such as stakeholder workshops (Menk, Terzi, *et al.*, 2022) aim to combine and generate knowledge to understand root causes for climate risks (Melo-Aguilar, Agulles and Jordà, 2022; Zebisch *et al.*, 2022) or to actively formulate criteria and weight factors for (regional) CRAs (Torresan *et al.*, 2016). A combination of national (ministries, agencies) and regional as well as private actors together with research institutions (meteorological, universities, etc.) allows pursuing a more holistic approach.

Challinor *et al.*, (2018) describe an interactive scenario building method for transboundary and trans-sectoral risks where stakeholder participation is expected to "examine the consequences of plausible futures, and test whether the current state of the system would be able to cope" (p. 14).

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An even more inclusive approach is described by Cavan and Kingston (2012) where a public participatory GIS-based tool for urban areas facilitates participation in climate change adaptation. The tool combines several (participatory) aspects by raising awareness, visualizing vulnerabilities and potentially supporting emergency responses.

However, it needs to be noted that an inclusive approach implies a proper connection between top-down and bottom-up approaches to integrate stakeholder perspectives accordingly. For this, Conway *et al.* (2019) discuss the possibility of giving stakeholders a top-down insight into e.g. climate impacts to facilitate a more conceptualized input regarding e.g. exposure units in exchange.

D. Pushing boundaries by bridging gaps in CRA

Recent research and conceptual developments in CRAs have revealed additional knowledge gaps in various areas. These gaps include understanding the societal dimensions of climate risks, such as trust, behavior, social norms, and culture (Challinor *et al.*, 2018; Menk *et al.*, 2022), estimation of residual risks (Adger, Brown and Surminski, 2018; Brown and Berry, 2022), systemic risk transmission across sectors and borders (Challinor *et al.*, 2018), identification of system critical points (Adger, Brown and Surminski, 2018; Challinor *et al.*, 2018), and more recently, maladaptation risks (Terzi *et al.*, 2019; Gallina *et al.*, 2020; Arribas *et al.*, 2022; Brown and Berry, 2022). Additionally, topics like low-likelihood, high-impact events (Sutton, 2019), and potential system reconfigurations (Brown and Berry, 2022) demand more attention.

CRA at sub-national levels also needs some methodological advancements regarding projections and simulations of future climatic and socio-economic changes (Jurgilevich *et al.*, 2017). This can be achieved by improving downscaling and computation techniques (Zscheischler, Westra, van den Hurk, *et al.*, 2018) or producing large regional ensembles that display local weather variability at the highest resolution possible (Sutton, 2019) or generating multi-model projections from multi-sector and multi-scenario input data (Rising *et al.*, 2022).

Traditional CRA methods seldom consider the behavior and perceptions of individuals, businesses, and government entities. Integrating individuals risk perception, societal behavioural dynamics, and other factors (e.g., collective memory, past hazard experiences, antecedent societal decisions, personal interests) influencing individual DRR choices into risk assessment highlights a critical gap that requires bridging methods from the natural sciences with the social sciences (Aerts *et al.*, 2018).

Overall, CRA needs to methodologically consider adaptation effectiveness (Adger, Brown and Surminski, 2018) and how adaptation measures influence risk dynamics and processes over time (Jurgilevich *et al.*, 2017). Furthermore, there is a need for more integrated studies that examine interactions of exposure, vulnerability, and hazards and their changes in space and time (Jurgilevich *et al.*, 2017; Lam and Lassa, 2017; Ronco *et al.*, 2017). Apart from these gaps, Menk, Schinko *et al.* (2022)

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identified the necessity to determine clear cause-effect relationships between climate impact and experienced well-being, as well as enhancing evidence (especially quantitative data) of avoided losses and damages. Also, Zebisch et al. (2021) highlight the gap due to the lack of a universally agreed definition of vulnerability and the need for making it more operational.

By comprehensively addressing these gaps and advancing research in these areas, CRAs can be more robust tools to effectively inform adaptation and resilience planning—ultimate purpose of CRA.

E. Reimagining CRAs

The CRA field still has a lot of room for development and exploration, with numerous opportunities for innovation and application (Table 3). The CRA community is undergoing a notable shift towards a more systemic perspective (UNDRR, 2022), integrating climate-related hazards to other threats, such as riverine floods, wildfires, and water contamination (Gallina *et al.*, 2020). For example, Hochrainer-Stigler *et al.* (2023) propose a framework to assess systemic risk by considering the interrelationships between multiple hazards and socio-economic dimensions, including climate-related risks.

To move towards a more robust CRA, the **next generation of assessments should adopt complex risk framing** (Simpson *et al.*, 2021). This involves incorporating adaptive and coping capacity indicators into the vulnerability considerations (Gallina *et al.*, 2020); responses and risk interactions as integral components of the risk analysis (Zscheischler *et al.*, 2018; Simpson *et al.*, 2021); and considering the multiple interactions among ecological, social and economic exposure and vulnerability drivers (Gallina *et al.*, 2020; Simpson *et al.*, 2021). It will also require providing the means to assess cross-sectoral and transboundary risks, as well as the influence of climate change on risk transmission mechanisms, including teleconnections, physical linkages, and feedback loops (Onyango *et al.*, 2016; Challinor *et al.*, 2018; Carter *et al.*, 2021; Simpson *et al.*, 2021; van den Hurk, Baldissera Pacchetti, *et al.*, 2023).

Moreover, CRAs can become more comprehensive by, for example, suggesting parameters to identify direct and indirect effects (Gallina *et al.*, 2020; Menk, Terzi, *et al.*, 2022), analyzing impacts of low-likelihood scenarios (Sutton, 2019), or progressing on the adaptation limits understanding through estimation of losses and damages (e.g. in functioning ecosystems, knowledge and education, physical and mental health, cultural identity, material living standards, and lifestyle) (Menk, Schinko, *et al.*, 2022).

To have more accurate risk characterization and improved evaluation of the effectiveness of risk-management strategies, it is crucial that future risk assessments examine how individuals and communities make investment choices in DRR and adaptation, how these choices ultimately impact the level of risks they face, how they are influenced by the outcome of CRAs, and how environmental

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(chronic) shocks reinforce a detrimental cycle of poverty and vulnerability (Aerts *et al.*, 2018). Also, future CRAs should be able to evaluate risk pathways in natural and human systems under different levels and rates of climate change and anthropogenic pressures (Terzi *et al.*, 2019; Zommers *et al.*, 2020). They should also consider the impacts of socio-economic pathways on risk dynamics and variability (Zommers *et al.*, 2020).

Improvements in climate risk and impact assessment methodologies are also necessary to support these advancements. Models should consider the influence of various non-climatic factors on future risks (e.g., population growth, land-use change, and development) (Conway *et al.*, 2019; Cremen, Galasso and McCloskey, 2022; Ruane *et al.*, 2022), correlations between natural and man-made hazards and climate change (Gallina *et al.*, 2020; Cremen, Galasso and McCloskey, 2022), and the distribution of elements at risk across space and time and the alteration of vulnerability over time (e.g., socio-economic dynamics, health conditions, ecosystem health, infrastructure integrity) (Terzi *et al.*, 2019; Cremen, Galasso and McCloskey, 2022; Ruane *et al.*, 2022).

Incorporation of uncertainty and risk factor sensitivity analysis is another important aspect that can improve the CRA usefulness for decision-making and adaptation planning (Terzi *et al.*, 2019; Gallina *et al.*, 2020; Melo-Aguilar, Agulles and Jordà, 2022), although the concept of *managing uncertainty* through e.g. an event-based storyline (Shepherd *et al.*, 2018; Sillmann *et al.*, 2021; van den Hurk, Baldissera Pacchetti, *et al.*, 2023) approach may provide remedy. Likewise, integrating quantitative, semiquantitative, qualitative, and narrative approaches can create a comprehensive view of risks (Dessai *et al.*, 2018; Menk, Terzi, *et al.*, 2022; Hochrainer-Stigler *et al.*, 2023; van den Hurk, Baldissera Pacchetti, *et al.*, 2023).

Further, integrating both top-down and bottom-up approaches in a continuous iterative process of data exchange, able to represent cause–effect dynamics, feedback relations and cross-connections, holds great potential for innovation (Conway *et al.*, 2019; Menk, Terzi, *et al.*, 2022). Here, consulting stakeholders during the formulation and representation of problems is essential (Peng *et al.*, 2021) as well as putting emphasis on a more transparent means to assess climate risks (Bressan *et al.*, 2022).

Other emerging innovation arenas in CRA **include utilizing citizen science, internet, and social media platforms** to collect vast amounts of data and indicators of risk (Challinor *et al.*, 2018), and more promising, the application of **Machine Learning in complex risk assessments** (Zennaro *et al.*, 2021).

Additionally, whereas CRA gives the idea of only providing information on risks, there is another school promoting the assessment of adaptation options and opportunities in the same CRA process (Reisinger *et al.*, 2020; Ruane *et al.*, 2022). By doing that, the assessment shifts from a problem-oriented piece to a solution-oriented assessment (Warren *et al.*, 2018). Including opportunities into

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the analysis of the changing climatic conditions can be beneficial to promote behavioral change and targeted action (Brown and Berry, 2022). For instance, taking adaptation options into the CRA can allow for a better understanding of the risk of doing "nothing" versus "something", and the effects and tradeoffs can be explored for a better-informed decision (Simpson *et al.*, 2021).

While the following considerations for CRA improvement emerge from scientific discussions in peer-reviewed literature, practitioners' perspectives remain scarce that, such as those examined as outcomes of co-production with practitioners in the UK's Climate Change Risk Assessments (CCRA 1-2) and whether they were "usable and/or used" (p. 87). Their results show that institutional and political context plays a decisive role while co-production does not necessarily lead to *usability* or *use*.

In summary, the field of CRA holds vast potential for innovation and development. With gaps to be bridged and new areas to be explored, it is crucial to reimagine CRA with a systemic perspective that integrates multiple hazards, considers risk interactions, and encompasses socio-economic dimensions. To that end, improved models and methodologies are needed, particularly concerning the integration or management of uncertainty and sensitivity analysis. By embracing these advancements, climate risks and their impacts can be better understood, while enabling more informed decision-making and more effective adaptation and resilience planning. Such opportunities call for collaboration across disciplines to exploit technology, data, and collective knowledge to not only reimagine, but also build a more comprehensive, dynamic, and effective approach to CRA.

Table 3. Reimagining CRAs – summary table.

Area of improvement	Opportunity	Source
Systemic perspective	Integration of climate-related hazards with other threats (e.g. water contamination).	(Gallina *et al.*, 2020)
	Examine interrelationships between multiple hazards and socio-economic dimensions.	(Hochrainer-Stigler *et al.*, 2023)
Complex Risk Framing	Inclusion of adaptive coping capacity indicators to vulnerability considerations.	(Gallina *et al.*, 2020)
	Inclusion of response and risk interactions in risk analysis.	(Zscheischler *et al.*, 2018; Simpson *et al.*, 2021)
	Inclusion of ecological, social and economic interactions in exposure and vulnerability drivers .	(Gallina *et al.*, 2020)
	Assess cross-sectoral and transboundary risks (risk transmission mechanisms, teleconnections, physical linkages, feedback loops).	(Onyango *et al.*, 2016; Challinor *et al.*, 2018 ; Carter *et al.*, 2021 ; van den Hurk *et al.*, 2023)
Adding comprehensiveness	Identification of parameters for direct and indirect effects.	(Gallina *et al.*, 2020; Menk, Terzi, *et al.*, 2022)
	Inclusion of low-likelihood scenarios.	(Sutton, 2019)

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Area of improvement	Opportunity	Source
	Understanding limits of adaptation for impact estimation.	(Menk, Schinko, *et al.*, 2022)
	Application of machine learning techniques for more complex analysis.	(Zennaro *et al.*, 2021)
Accuracy	Monitoring and tracking DRR and adaptation investment choices, their impacts on risks and CRAs influence on them.	(Aerts *et al.*, 2018)
	Understanding on the relationship between environmental shocks and poverty and vulnerability.	(Aerts *et al.*, 2018)
	Assessment of risk pathways under different levels and rates of climate change and socio-economic dynamics.	(Terzi *et al.*, 2019; Zommers *et al.*, 2020)
Broadening perspectives	Managing uncertainty by integrating uncertainty and risk factor sensitivity.	(Shepherd *et al.*, 2018; Terzi *et al.*, 2019; Gallina *et al.*, 2020; Sillmann *et al.*, 2021; Melo-Aguilar, Agulles and Jordà, 2022; van den Hurk, Baldissera Pacchetti, *et al.*, 2023)
	Integration of semi-quantitative, qualitative, and narrative approaches.	(Dessai *et al.*, 2018; Menk, Terzi, *et al.*, 2022; Hochrainer-Stigler *et al.*, 2023; van den Hurk *et al.*, 2023)
	Inclusion of top-down and bottom-up approaches as an iterative process (data exchange, cause-effect dynamics, feedbacks, cross connections) with stakeholder consultations.	(Conway *et al.*, 2019; Menk, Terzi, *et al.*, 2022; Peng *et al.*, 2021)
	Inclusion of citizen science, internet and social media platforms.	(Challinor *et al.*, 2018)
Models robustness	Inclusion of non-climatic factors on future risks (e.g. population growth, land-use change, development).	(Conway *et al.*, 2019; Cremen, Galasso and McCloskey, 2022; Ruane *et al.*, 2022)
	Correlations between natural and man-made hazards in climate change.	(Gallina *et al.*, 2020; Gallasso and McCloskey, 2022)
	Distributional aspects (time and space) of elements at risk and vulnerability (e.g., socio-economic dynamics, health, infrastructure integrity).	(Terzi *et al.*, 2019; Cremen, Galasso and McCloskey, 2022; Ruane *et al.*, 2022)
Alternative directions	Inclusion of adaptation options and opportunities in CRA possibly providing new windows and behavioral change.	(Reisinger *et al.*, 2020; Ruane *et al.*, 2022 ; Warren *et al.*, 2018; Brown and Berry, 2022)

3.2. National and regional risk assessments and Union Civil Protection Mechanism

3.2.1. The Union Civil Protection Mechanism and risk assessments

After reviewing challenges and opportunities of running CRA as documented in the peer-reviewed literature, we now turn to looking at the practice of using CRA for different purposes, for which we start with CRA for the Union Civil Protection Mechanism.

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The Union Civil Protection Mechanism (UCPM) is an EU framework promoting collaboration on civil protection to improve prevention, preparedness, and response to disasters. It fosters collective capacity to manage natural, technological, and health hazards, embodying the EU's commitment to solidarity as mandated by the Treaty on the Functioning of the European Union (TFEU). During disasters, it operates as a resource, expertise, and knowledge hub, coordinating emergency assistance and facilitating requests for and provision of international assistance.

Through a Council Decision in 2001 (2001/792/EC, Euratom – no longer in force) a community mechanism was established to facilitate reinforced cooperation in civil protection assistance interventions. It underwent sizeable changes and was recast in 2007 to improve its effectiveness. More substantial transformation took place in 2013 when the mechanism was thoroughly reformed and replaced as Decision No 1313/2013/EU of the European Parliament and the Council, thus establishing the UCPM. This 2013 Decision, amended twice, first in 2019 and then in 2021, serves as the current legislative framework of the Mechanism. The 2019 amendment added rescEU, a reserve of European capacities, including, among others, firefighting planes and helicopters, medical evacuation planes, stockpile of medical items and field hospitals, as well as emergency medical teams. These resources are an additional layer of protection available and provide faster and more comprehensive response to support countries, especially in the case of simultaneous events that undermine the ability of member states and UCPM participating states to help each other. The 2021 amendment introduced several features, notably the Union Civil Protection Knowledge Network. This hub was set up as a tool of the UCPM with the aim of strengthening the effectiveness of civil protection training and exercises, promote innovation and dialogue, and enhance cooperation between countries' national civil protection authorities. It involves a collaborative effort between experts from civil protection, disaster risk management, first responders, and academic institutions, aiming to synthesize, develop, and disseminate knowledge products relevant to the Mechanism and work together.

The UCPM mandates national and sub-national risk assessments, risk management planning, and assessment of risk management capabilities (Article 6). Member states and participating states are also encouraged to engage in voluntary peer reviews of their risk management capabilities. **National risk assessment** (NRA) refers to the systematic process of identifying, analysing, and assessing risks that could potentially lead to emergencies or disasters. It involves comprehensive evaluations of various factors, including natural and human-induced hazards. As early as 2009, the European Council invited the Commission and the Member States to conduct a systematic assessment of risks and provide a synthesis thereof every three years. The 2021 UCPM amendment emphasized key risks with cross-border impacts, risks related to disasters causing multi-country transboundary effects, and low probability risks with high impact, for which priority prevention and preparedness measures should be elaborated. **Risk management capability** denotes capacity to reduce, adapt to or mitigate

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risks identified in risk assessments to acceptable levels. It encompasses the technical, financial, and administrative abilities to conduct risk assessments, develop risk management plans, and implement risk prevention, preparedness, response, recovery and lessons learned measures.

The most recent amendment of the UCPM decision introduced two key enhancements to the EU's risk management capabilities for addressing cross-border effects: **Union disaster resilience goals** and **cross-sector disaster scenarios**. The resilience goals, non-binding targets for boosting capacity to manage cross-border disasters, were defined in five areas in the 2023 Communication. These include anticipating risks through improved assessment and threat anticipation; enhancing preparedness through risk awareness and readiness; improving early warning systems for timely alerts; strengthening response capacity within the UCPM to assist when a country's capacity is overwhelmed; and maintaining a robust civil protection system that ensures operational readiness, updates continuity plans, promotes coordination, and facilitates information sharing. Cross-border and cross-sector disaster scenarios, currently under development, encompass both natural and man-made drivers including climate change, and provide input for comprehensive disaster prevention, preparedness, and response planning and management.

The **peer review of risk management capabilities** is a process through which UCPM and European Neighborhood Policy East and South countries assess each other's capacities, procedures, and overall performance in the field of civil protection and disaster risk management. During the peer review process, countries share best practices, exchange knowledge, and provide constructive feedback to enhance their respective civil protection systems. Peer reviews, rooted in transparency, trust, mutual assistance, and continuous learning, aim to identify strengths and areas for improvement, share experiences and lesson learned, and identify innovative approaches to manage risks. To date, fifteen countries have completed the peer review process.

3.2.2. Overview of UCPM national risk assessments in the CLIMAAX pilot areas

This section provides a summary of the national risk assessments (NRAs) for the five pilot countries/regions involved in the CLIMAAX project. The pilots in Finland (FI) and Latvia (LV), both located in the boreal biogeographical region, are defined at the national level. The pilots in the Mediterranean biogeographical region on the Iberian Peninsula, namely Catalunya (Spain, ES) and Setubal (Portugal, PT), are defined at the regional and local levels respectively. Lastly, the Slovakian (SK) pilot, situated in the Alpine biogeographical region, is analysed at the local/municipal level (Zilina city). The concise reviews concentrate on the rationale behind identifying and evaluating key risks, collaboration between national and subnational government levels, and available data sources when applicable. An overview of the risk assessment process in the various pilot areas is provided in Table 4.

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In 2013, **Finland** was among the initial countries to partake in the UCPM Peer Review Program for risk management capabilities. The review aimed to enhance the Hyogo Framework for Action's implementation and reporting, foster consistency in national disaster risk policies, contribute to EU disaster risk management initiatives, promote stakeholder engagement and transparency, and stimulate policy dialogue and regional collaboration among countries with shared hazards and risks. One of the peer review's conclusions was the need to improve National Risk Assessments (NRAs) through a more comprehensive and coordinated approach, spanning from national to local levels. This includes enhancing methodologies for large-scale risk assessments and harmonizing regional assessments. As a result, the government revamped its risk assessment process, with the first NRA completed in 2015. The second NRA was published in 2018, followed by the release of the third NRA in 2022-2023.

The nationwide risk assessment system includes national and regional assessments[1] that identify and evaluate significant risks across sectors. Organizations and sectors develop their own risk assessments tailored to their tasks, operations, and legal obligations. Cross-sectoral regional risk assessments involve collaboration with municipalities, wellbeing services counties, authorities, businesses, and organizations. The findings and process of regional risk assessment are compiled into a report shared with regional operators and stakeholders, serving as a guiding principle for their preparedness alongside the national assessment.

The NRA is developed by central government ministries, the Emergency Supply Agency, the Finnish Meteorological Institute, representatives from the Regional State Administrative Agencies, and the Finnish Red Cross. It focuses on rapid-onset events impacting national security and critical societal functions, requiring nationally coordinated crisis management and international assistance. The assessment identifies and examines 21 significant threat scenarios affecting vital societal functions, and analyse their realization, targets, and impact. It also acknowledges threats originating within and outside the country, including climate-related risks and their interdependencies with global supply chains and other risk pathways. Both physical and transition climate related risks are acknowledged. Physical climate risks and associated threat scenarios are primarily considered relevant at the regional level and are therefore addressed within the framework of regional risk assessments. Climate-related risks play a significant role in several of the 21 national threat scenarios, including **large-scale wildfires, food and nutrition, water supply disruption, health security, and energy supply and transportation disruption scenarios**. Threats and disruptions are evaluated based on their impact on vital societal functions and strategic tasks outlined in the National Security Strategy. The impact assessment spans from minor to severe, while likelihood is determined through implicit expert judgment.

In **Latvia**, risk assessments based on common methodology are enshrined in the Civil Protection and Disaster Management Law as a joint responsibility of competent risk management authorities. Na-

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tional Risk Assessment is embedded in the National Civil Protection Plan, monitored annually, revised every four years, and includes outcomes of a multi-hazard risk assessment. The NRA identifies key risks, including **floods, forest fires, storms, nuclear accidents, accidents at sea, extreme weather impacting critical infrastructure**, and pandemics. Low probability - high impact types of events are assessed based on historical data. NRA developed by ministries and their subordinate institutions and experts are then to be included in the National Civil Protection Plan done by the State Fire and Rescue Service of Latvia. According to the risk assessment and analysis done, national and local authorities shall plan disaster management measures (prevention, preparedness and response activities) that are to be included in the National Civil Protection Plan and serve as a basis for the comprehensive disaster management system.

Spain has reported two national risk assessments in 2015 and 2021. These assessments are developed within the National Civil Protection System (SNCP), which involves various public bodies at the state, regional, and local levels, including the National Geographical Institute, Hydrographic Surveys, National Meteorology Agency, Geological and Mining Institute of Spain, Spanish Institute of Oceanography, and others. Assessment of various risks is based on a range of hazard-related guidance and unified methodologies and plans. The NRA is structured in form of risk catalogue defined in Law 17/2015. It includes risks such as **flooding, forest fires,** earthquakes, tsunamis, volcanic eruptions, **adverse weather events**, accidents involving hazardous substances, civil aviation accidents, transportation of dangerous goods, nuclear and radiological incidents, and risks related to war. The national and regional authorities have conducted extensive risk assessments and produced hazard maps used for territorial zoning. The National Civil Protection Information Network (RENAIN) serves as a comprehensive repository of data on various risks and their corresponding response strategies. The Civil protection strategy identifies several megatrends contributing to exacerbating the risk, including **climate change**, poor spatial planning, environmental degradation, globalization, and socio-economic constraints. Key **cross-border risks include forest fires, dam failures, and floods,** which can have significant impacts across national boundaries. Additionally, there are low probability-high impact events such as tsunamis, industrial accidents, and nuclear and radiological risks that require attention and preparedness measures. The summary of the National Risk Assessment (NRA) includes hazard maps but without specific details regarding the methodologies and data used in the assessment.

In **Portugal**, NRA is coordinated by the Portuguese National Authority for Emergency and Civil Protection (ANEPC). ANEPC oversees the assessment processes at the national and intermediate levels, while municipalities and Regional Civil Protection Services handle local and regional assessments, respectively. The private sector holds legal responsibilities for specific risk assessments, such as chemical accidents and dam failures. NRA was first produced in 2014 and updated in 2019 to include

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updated records and revised risk scenarios. The assessment identified 24 risks originating from natural, man-made, or mixed sources. Probability, impact, and risk levels are assessed using 5-point scales. Likelihood is determined based on either the annual probability or the return period, with a scale ranging from a return period of less than once in 5 years to more than once in 200 years. Similarly, the impacts of risk scenarios are classified into different levels, ranging from residual (low) to critical. Critical impacts may involve significant casualties, permanent environmental damage, and substantial disruptions to society. The NRA identifies various key risks, **including rural fires, heat waves**, earthquakes, tsunamis, **droughts, windstorms**, dam breaks, radiological emergencies, and **floods**. These are risks categorized as "extreme" or "high" risk. Portugal shares several risks with Spain due to their geographic and meteorological/geological conditions, resulting in potential cross-border impacts. Rural fires, dam breaks, and floods originating from either country can have adverse effects on the neighbouring nation. Climate change scenarios indicate a potential increase in the frequency and impact of meteorological risks in Portugal. The 2019 NRA does not extensively assess emerging risks like vector-borne diseases, biodiversity loss, and cyber-risks. However, the importance of these risks may increase over time, leading to their inclusion in future assessments.

Slovakia has submitted two national risk assessments, in 2015 and 2020. These assessments are based on a territorial register of potential threats to life, health, property, and the environment. The register is developed at various territorial governance levels and involves the expertise of professionals in crisis management. Methodological guidance provided by the Ministry of Interior is used to complete and summarize the register for the purpose of the NRA. The 2015 National Risk Assessment (NRA) provides a comprehensive description of threats and their causal impacts, while the 2020 NRA serves as an updated version, covering all risks and identifying key risks. The most common risks in the territory of the Slovak Republic include **floods**, including **more frequent pluvial and flash floods in recent times, landslides, snow calamities, windstorms, fires** and hazardous substances incidents, including leaks, explosions, and landfill findings. The identification and assessment of risks is based on qualitative methodology, assigning numerical values to likelihood and impacts, and successively multiplying them to generate a risk score. The likelihood rating scale ranges from 1 to 3, with 1 representing rare events that occur less than once every hundred years and 3 representing frequent events that occur approximately once every second year. Likewise, the impact rating scale from 1 to 3 indicates the significance of impacts, with 1 representing impacts at the local level, 2 indicating impacts at the regional level, and 3 signifying impacts at the national level. Risks with scores equal to or greater than 6, obtained by multiplying the likelihood and impacts, are considered very high or unacceptable. Risks with scores ranging from 3 to 4 are considered moderate, while risks with scores less than 3 are classified as low. The temporal evolution of risks is assessed in conjunction with the impact of economic, social, and environmental megatrends. Two levels, namely low and significant, are used to categorize the impacts of these megatrend on the identified risks. The regional and local assessment of risks relies on historical data related to

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damage, losses, and the magnitude of observed disruptions. Using this methodology, the 2020 National Risk Assessment (NRA) identifies a total of 62 hazards, out of which 25 are classified as key risks. A majority of these key risks (20 out of 25) are amplified by **climate change**. Additionally, 21 of these key risks are considered to have cross-border effects. The NRA also identifies 17 low probability - high impact types of events. The hazards are classified in natural – biotic, abiotic and space-related, man-made or technological, social or sociogenic and economic. The social threats include disruption of social and healthcare provision system and disruption of the provision of emergency assistance. The economic threat includes disruption of the monetary, foreign exchange, and financial economy of the state.

Table 4. Overview of the risk assessment process in the five pilot areas.

Country	Risk assessment system	Governance & involved actors	Risk assessment approach
Finland	Three NRAs produced (2015, 2018, 2022-2023). National/regional risk assessments to identify cross-sectoral risk. Organizations and sectors with own risk assessments. Cross-sectoral risk assessments involving municipalities, wellbeing service counties, authorities, businesses, other organizations. Risk assessment report as guidance.	Central government ministries, Emergency Supply Agency, Finnish Meteorological Institute, Regional State Administrative Agency representatives, Finnish Red Cross	Identification of 21 threat scenarios (realization, targets, impact) with inclusion of climate-related risk e.g. interdependencies with global supply chains or other risk pathways. Physical climate risks tackled in regional risk assessments. Evaluation of threats based on impact assessment.
Latvia	Legal basis: Civil Protection and Disaster Management Law. NRAs are to be included in National Civil Protection Plan including disaster management measures.	NRA development by ministries, subordinate institutions and experts.	Civil Protection Plan includes multi-hazard risk assessment. Identification of key risks; disaster management measures according to risk assessment.
Spain, **Catalunya**	Two NRAs reported (2015, 2021). NRAs developed within National Civil Protection System (SNCP). Risk catalogue defined by law. Civil Protection Strategy identifies trends which may lead to exacerbation of risk, including climate change aspects.	State/regional/local authority, National Geographical Institute, Hydrographic Surveys, National Meteorological Agency, Geological and Mining Institute, Spanish Institute of Oceanography etc. National Civil Protection Information Network owning risk data and response strategies.	Unified methodology and plans with hazard-related guidance. Risk assessment conducted with emerging hazard maps. Identification of key cross-border risks.
Portugal, Setubal	One NRA produced in 2014 with update in 2019.	National and intermediate-level NRAs coordinated by National Authority for Emergency and Civil Protection (ANEPC); regional/local NRAs by municipalities and	Identification of 24 risks originating from natural, man-made or mixed sources. Assessment of probability, impact and risk through scales. Likelihood determination by probabilities and/or return period (5-200 years). Impacts of

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		civil protection services. Additionally private sector carries out specific risk assessments.	risk scenarios ranging from residual to critical. Consideration of cross-border risks and impacts (Spain).
Slovakia, Zilina city	Two risk assessments submitted (2015, 2020).	Threat register developed by various governance levels and experts; methodological guidance by Ministry of Interior.	NRA based on territorial register of potential threats to life, health, property and environment. 2015 NRA describes threats and impacts; 2020 NRA covers all risks and identifies key risks with climate change aspects. Likelihood and impact assessment based on scale (1-3); multiplication to generate risk score. Risks considered together with economic, social and environmental trends.

3.2.3. Lessons learned from national risk assessments across Europe

The NRAs from the CLIMAAX pilot countries demonstrate **various approaches for identifying and analysing key risks and assessing their consequences**. These assessments are closely aligned with national security or civil protection strategies and plans, and they consider a range of hazard threats, including those that are intensified by climate change. Collaboration among national and subnational organizations involved in risk management is a common element in all NRAs. However, there are differences in how risk scenarios are developed. Some countries provide a summary of the impacts of climate-related risks, while others conduct a more detailed assessment of situations that could undermine resilience or create crises requiring coordinated management. While most NRAs identify multiple and cross-border risks, more sophisticated NRAs also describe how risks can interact and spread across geographic and sectoral boundaries.

The European Commission (EC) produced summary overviews of natural and man-made disaster risks in 2014, 2017, and 2020, building on Member States' NRAs from 2012, 2015, and 2018. A summary report based on the 2020 NRAs is currently being finalised. Complementing these overviews, the Joint Research Centre (JRC) has issued its own risk evaluation and several guidance documents, while the Organisation for Economic Co-operation and Development (OECD) published an overview of National Risk Assessments in certain countries.

The latest published report is the 2020 Summary of the third round of National Risk Assessments submitted in 2018. The European Commission acknowledged the gradual progress and improved methodologies underlying the assessment. However, the maturity and scope of risk assessment work vary across Europe, reflecting diverse approaches and levels of development. National risk assessments vary in coverage, making achieving a comprehensive EU-level assessment challenging.

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Some focus on natural hazards, while others encompass technological accidents and a wide range of threats, including malicious intent, economic risks, social unrest, and military threats. Differences in NRAs reflect institutional structures and the distribution of responsibility at the national level.

Certain risks, including geophysical risks, drought, nuclear or radiological accidents, influx of refugees and migrants, and emerging risks, have received increased attention throughout reporting cycles. The coverage and knowledge regarding risks such as flooding events, extreme weather scenarios, and wildfires have been extended and improved. Growing concern about epidemics and health risks was noted before the COVID-19 pandemic.

National risk assessments vary in their focus, with some predominantly considering past natural hazards and others encompassing the changing security environment and its implications for man-made threats. There is a growing recognition of the interdependence and complexity of risks, leading to broader societal security perspectives and multi-hazard/multi-risk analyses. Such assessments enhance understanding and inform prevention and preparedness efforts. However, challenges remain in assessing cross-sectoral interdependencies and cross-border/regional/international dimensions of risks, which are not extensively addressed in national assessments. To incorporate a forward-looking perspective, national risk assessments increasingly consider factors like climate change, demographic developments, migration trends, technological advances, globalisation, and international relations. This forward-looking approach is crucial for strategic planning, long-term investments, and immediate preparedness and response measures.

Approximately half of the reports used **climate models and projections** to analyse disaster risks, considering future scenarios up to 2050 and/or 2100. Some Member States specifically compared current and future risks in the context of climate change. National authorities responsible for climate change actively participated in the risk assessment process, referencing existing climate risk assessments and adaptation strategies. The recent amendments to the UCPM legislation highlight the importance of enhancing preparedness for low probability events with severe consequences, including those amplified by climate change and systemic interdependencies. This demonstrates a stronger focus on anticipating and addressing transboundary extreme events at the EU level. Assessing low-probability events with catastrophic consequences have received limited attention so far, also due to their rarity and lack of historical data or experience. Decision-making processes may deprioritize these extreme scenarios. However, low-probability risks with high impact present significant challenges for prevention and preparedness as the costs of both action and inaction can be significant. Investing in collective resilience and risk reduction measures becomes essential to protect against the potential magnitude of their impact.

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3.3. Risk assessments in national and international policy dialogue

The ongoing shift towards a risk approach in Climate Change Adaptation in the scientific community is partly noticeable in national documents, plans and strategies. For this, three types of key policy documents for national and international policy dialogue are reviewed (Table 5) to examine role, importance and comprehensiveness of the risk concept and to identify remaining gaps. In section 3.3.1 European National Adaptation Plans (NAP) and policy framework-setting National Adaptation Strategies (NAS) are reviewed, followed by the national Sendai Framework Mid-Term Reviews (MTR) in section 3.3.2.

It needs to be noted that although the reviewed documents were the latest available, some date back to the early 2010s. This implies that climate risk assessments may have been conducted in the meantime, although there is no reference given in the documents. This is e.g. the case in Germany where the NAS was published in 2020 while a Climate Impact and Risk Assessment followed in October 2021 (Kahlenborn *et al.*, 2021). What this section aims to show is if and how risk and adaptation considerations are connected.

Table 5. Consideration of CRA in reviewed National Adaptation Strategies (NAS), National Adaptation Plans (NAP) and Sendai Mid-Term Reviews (MTR) of EU- and relevant non-EU-countries

	Countries of the European Union																											non-EU			
	AT	BE	BG	HR	CY	CZ	DK	EE	ES	FI	FR	DE	GR	HU	IE	IT	LV	LT	LU	MT	NL	PL	PT	RO	SK	SI	SE	CH	LI	NO	UK
NAS	✓	✓	✓	(*)	(*)	(*)	✓	✓		✓	(*)	✓	(*)	(*)	✓	✓	(*)	(*)	(*)	✓	✓	(*)	(*)	(*)	(*)	✓	(*)	✓	✓	✓	(✓)
NAP	✓	✓	(✓)	(*)	(*)	(*)	✓	(*)	✓	✓	(*)	(✓)			✓			(*)	(*)		✓			(*)			(*)	✓			✓
MTR	✓	✓																				✓				✓	✓	✓		✓	

The symbols refer to the availability of the documents:
✓ - available in English and reviewed, (✓) – available within NAP/NAS and reviewed, (*) – available, not in English, (empty) – unavailable. The colors imply the role of risk assessments for the respective documents, if they explicitly refer to a CRA (dark green) or somehow include (the concept of) CRA in the document for the present or future (light green), while white coloring suggests CRA does not play a role in these types of documents (if reviewed).

3.3.1. Risk considerations in NAPs and NAS

Risk **considerations in NAPs and NAS vary significantly** and remain far from a joint, standardized approach. From 32 revised documents from 19 countries, only few explicitly refer to climate risk assessments as a (partial) basis of the NAP/NAS such as e.g. the Climate Change Risk Assessment CCRA1-3 in the United Kingdom (see color coding in Table 5). Most adaptation plans and strategies lack a conceptual and/or practical risk section, and, therefore, risk is usually being addressed only indirectly in the documents. Here, the NAPs/NAS follow a similar pattern through categorization of important sectors with risk considerations according to relevant hazards.

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If risk is defined quantitatively, in most cases it is not consistent with risk conceptualization of the IPCC SREX (IPCC, 2012) or AR5 (IPCC, 2014) according to which risk is a product of *hazard*, *exposure* and *vulnerability*. A reason for this might lie in the relatively early origin of some documents where a broad, common risk language and conceptualization was still missing. Only the NAS of Bulgaria (Dale *et al.*, 2019) and the NAP of Spain (Government of Spain and Spanish Ministry for Ecological Transition and Demographic Challenge, 2020) actively refer to risk as the interplay of *hazard*, *vulnerability* and *exposure* according to IPCC AR5.

Box 2. Risk integration and conceptualization.

Good practice example for risk integration and conceptualization

Some adaptation plans and strategies follow a different approach. The **United Kingdom** uses an integrative risk assessment with sectoral considerations and a specific risk section for every sectoral NAP chapter (Department of the Environment, Food & Rural Affairs of the United Kingdom, 2018) while building on national Climate Change Risk Assessments (CCRA1 & CCRA2).
The NAP of **Switzerland** combines hazard, and implicitly vulnerability and exposure in the concept of *challenges* emerging from climate change in nine sectors and shows a graphical risk presentation of the challenge or underlying hazard (Swiss Confederation, 2020).
Germany follows a risk- instead of hazard-based approach for their adaptation strategy (Government of Germany, 2020).
The **Netherlands** address six urgent climate risks for their country, thus setting risk considerations as the basis for adaptation (Dutch Ministry of Environment, 2016).

Box 3. Ex ante risk reduction.

Good practice example for commitment to *ex ante* risk reduction

Norway's NAS (Norwegian Ministry of Climate and Environment, 2012) explicitly values *ex ante risk reduction* over *ex post* actions.

Another important aspect of risk consideration in the reviewed documents is **financial and economic risk** in the adaptation context of climate change. Many countries have recognized that these types of risks triggered by climate change can be partially tackled through risk transfer via insurance (e.g. Government of Denmark, 2008; Ministry of Agriculture and Forestry Finland, 2014; Government of Germany, 2020). Particularly for Bulgaria (Dale *et al.*, 2019), climate change is considered to pose a big risk to the national and local economy, thus endangering economic wellbeing.

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Many documents refer to possible **social impacts** through climate risk. However, this happens at different levels. For instance, the NAS of **Ireland** (Irish Department of Communications, Climate Action and Environment, 2018), **Germany** (Government of Germany, 2020), **Bulgaria** (Dale *et al.*, 2019) and **Norway** (Norwegian Ministry of Climate and Environment, 2012) consider climate change impacts on the lowest socio-economic and demographic groups, or the Finnish NAP includes "population groups and livelihoods with the weakest adaptation capacity" (Ministry of Agriculture and Forestry Finland, 2014, p. 21). The **Austrian** NAS claims to be "the only strategy in Europe which considers social aspects" (Kronberger-Kießwetter, Balas and Prutsch, 2017, p. 29) such as effects of "gender and group-specific aspects in dealing with natural hazards" (ibid., p 54). Before 2017 a thorough reflection of social impacts in national adaptation documents is indeed quite rare, however, more recent documents caught up.

Box 4. Social vulnerability.

Good practice example for social vulnerability

The NAP of **Spain** (Government of Spain and Spanish Ministry for Ecological Transition and Demographic Challenge, 2020) distinguishes between two vulnerabilities emerging from climate change: Territorial and social vulnerability. The latter refers to the unequal, actual and potential impacts of climate change due to sociodemographic variables such as age, sex, education or income level. In the document the integration of a gender focus in the adaptation process is also touched.

Attention given to risk drivers hazard, exposure, vulnerability

Hazard takes a dominant role in the reviewed adaptation plans and strategies as it seems easy comprehensible and can be considered according to necessity and geomorphological challenges in the respective country. Usually, the documents mention important hazards for respective sectors, which lead to a list of rapid and slow-onset events (Box 5).

Box 6. Inclusive risk framing.

Good practice example for an inclusive risk framing

In their NAS the **Netherlands** established an overview of climate change risks in four *effects diagrams* (Dutch Ministry of Environment, 2016). The diagrams are divided by climate hazard threats *warmer – wetter – drier – rising sea level* and include climate change trends in combination with risks (or opportunities) for vulnerable and exposed sectors.

Box 5. Hazards mentioned in NAPs and NAS.

Rapid events

Flooding, heavy precipitation, drought, heat waves, wind & storms, blizzards, hail, rockfall & erosion, wildfire, diseases & pathogens as well as increasing extreme weather events in general.

Slow-onset events

Increasing temperatures, rising sea level, glacier melting, erosion, ocean acidification.

While hazard maps are a common basis for national adaptation plans and strategies (e.g. Norwegian Ministry of Climate and Environment, 2012; Government of Liechtenstein, 2018) references to and

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inclusion of national **vulnerability and exposure assessments** and/or maps is still rare in the reviewed documents. Again, this can be partially traced back to the conflicting conceptualization of risk, hazard, vulnerability and exposure in NAPs and NAS.

In most reviewed documents ***exposure* and *vulnerability* are difficult to distinguish**, as the sectoral hazard approach rarely allows a clear distinction of concepts. Therefore, exposure (and potential vulnerability) is usually considered indirectly within sectors or according to hazards. One applied example for this issue is described by the *Heat Island Effect* in cities which is considered in the NAS of Austria and the NAP of the Swiss Confederation (Kronberger-Kießwetter, Balas and Prutsch, 2017; Swiss Confederation, 2020), where *hazard, exposure* and *vulnerability* meet.

Box 7. Inclusion of vulnerability assessment.

Good practice example for vulnerability assessment as part of NAS

AS of 2018 all member countries of the **European Union** had carried out a national vulnerability assessment, except for Poland (European Environment Agency, 2018). **Germany** mentions its cross-sectoral vulnerability analysis to climate change (Buth *et al.*, 2015) in its NAS, thus actively connecting vulnerability with risk in an adaptation context.

Box 7. National risk assessment tool.

Good practice example for an online risk assessment tool

The **Austrian** NAS (Kronberger-Kießwetter, Balas and Prutsch, 2017, p. 96) refers to an online platform for natural hazards and risk detection (HORA) which can be used by all citizens to obtain “an initial risk assessment of various natural hazards and weather events (such as flooding, earthquakes, storms, hail, lightning, and snow load) simply by entering an address”.

Considering adaptation and responses

Many national adaptation strategies and plans mention *concrete* response and adaptation options, e.g. NAS of **Finland**, NAS/NAP of **Austria**, NAS of **Italy**, NAS of **Germany**. Generally, response and adaptation considerations in the reviewed documents provide more concise information about the practical implications of risk by mentioning e.g. mitigation-adaptation synergies (Italian Ministry of Environment, 2015) or nature based solutions and a circular economy as cross-cutting option (Government of Spain and Spanish Ministry for Ecological Transition and Demographic Challenge, 2020). Also, the issue of maladaptation is being mentioned or discussed, leading to new types of risk (Belgian National Climate Commission, 2010; Spanish Office for Climate Change, Spanish State Secretary for the Environment and Spanish Ministry of Agriculture, Food and Environment, 2014; Kronberger-Kießwetter, Balas and Prutsch, 2017).

Technical implementation choices

Risk conceptualization in NAPs and NAS rarely becomes specific regarding technical implementation choices. To evaluate prevailing information about technical implementation the variables *risk metrics, scenarios and time horizon, impact pathways* and *quality assurance* were investigated.

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- **Risk metrics:** In its NAS Finland states that it was "(…) difficult to find a common metrics for the evaluation and comparison of the disadvantages, advantages or risks" (Ministry of Agriculture and Forestry of Finland, 2005, p. 10). While Finland's NAS is the oldest reviewed document in the selection of plans and strategies, the following documents only slightly dive more into this. Especially extreme events, particularly floods, are considered probabilistically with return periods.
- **Climate scenarios:** While not all plans and strategies refer to *climate scenarios* or *time horizons*, most of them use either the old (B1 – A1F1) or newer (RCP2.6 – 8.5) IPCC emission scenarios. Denmark (Government of Denmark, 2008) also integrates the 2°C climate scenario for Europe (EU2C). Switzerland refers to the CH2018 climate scenarios established by ETH Zürich and regional climate models (Swiss Confederation, 2012, 2020). Austria explicitly focuses on hazard and spatial planning as "future climatic changes are not considered at present in the basis of calculation" (Kronberger-Kießwetter, Balas and Prutsch, 2019, p. 201).

Box 8. Climate scenarios.

Good practice example for the value of climate scenarios

The **Belgian** NAP (Belgian National Climate Commission, 2016) considers coherent climate scenarios as foundation for good risk assessment, thus explicitly setting a theoretical risk approach and linking it to national adaptation processes.

- **Time horizons:** As most documents refer to IPCC emission scenarios, the time horizon of 2100 seems to be (implicitly) acknowledged when it comes to climate scenarios. However, they were usually not explicitly specified. Adaptation implementation and action plans vary greatly from specific years to decades or the year 2100. If time horizons are set, *short*, *medium* and *long term* responses are defined differently. For example, the German NAS (Government of Germany, 2020) vows for a long-term preparedness including a resilience increase but a short-term crisis management for immediate and extreme events.

Box 9. Time horizons.

Good practice example for the value of time horizons

The **Austrian** Adaptation Plan (Kronberger-Kießwetter, Balas and Prutsch, 2019) as well as the Adaptation Strategy of Liechtenstein (Government of Liechtenstein, 2018) explicitly mention differing time horizons for differing sectors due to possibilities and needs.

- **Impact chains:** The identification of impact chains in the documents shows that – although most documents performed poorly in their risk conceptualization – risk does play a role in adaptation considerations, however an implicit one. Impact chains are usually directly (and indirectly) considered within sectors due to the dominant sectoral approach of NAPs and NAS. Some of the documents also gave thought to the systemic aspects of risk and cross-sectoral impact chains with cascading effects/failures as well as economic inter-dependencies, partly beyond the country level and with international feedbacks. Especially the NAS of

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Austria (Kronberger-Kießwetter, Balas and Prutsch, 2017) acknowledges the cross-sectoral complexity of adaptation and therefore risk. Also, the Dutch NAP and NAS touch upon cumulative and knock-on climate effects, which, however, need more attention according to the document. It needs to be noted, that none of the documents treated this complex issue in a comprehensive way but rather as an additional perspective which needs to be regarded in the future.

- **Quality assurance:** The last section of technical implementation choices concerns the quality assurance of risk considerations in NAPs and NAS. Most documents explicitly mention an orientation on EU legislation or international standards (Box 10). Besides these quality assurance documents, many NAPs and NAS refer to international agreements or frameworks like the Hyogo Framework of Action 2005-2015 (e.g. Bulgaria, Italy), the Sendai Framework for Disaster Risk Reduction 2015-2030 (e.g. Germany, Netherlands), the Warsaw International Mechanism on Loss and Damage (e.g. Italy), the Paris Agreement (e.g. Ireland, Austria) and the UN Sustainable Development Goals (e.g. Germany, Ireland). Especially after 2014 a growing IPCC influence was noticeable due to an increased number of attributions in the documents (e.g. Austria, Norway, Finland).

Box 10. Legal and international standard quality assurance orientation mentioned in NAPs and NAS.

Quality assurance orientation

- EU Water Framework and Floods Directive 2007/60/EC

- EU Risk Assessment and Mapping Guidelines for Disaster

- ISO 310000, ISO 14090, ISO 14001

Governance aspects

While the technical implementation choices remain rather broad and undefined, governance actor and stakeholder involvement allow for more insights in the structure and planning of NAPs and NAS. Although the governance analysis concerns adaptation processes, risk is scattered throughout the documents, thus making part of the adaptation process according to the different countries. Also, as adaptation plans and strategies ideally build on risk assessments, a clear, however unspecified, link exists. Overall, (environmental) ministries (e.g. Norway, Malta) are the main actors in the reviewed documents. Sometimes an inter-ministerial cooperation (e.g. Slovenia), leading federal offices (e.g. Switzerland) or involvement of the prime minister's office (e.g. Finland) is mentioned. Most countries established – or plan to establish – committees, special offices or working groups according to their NAP/NAS.

In most NAPs and NAS the official state actors work together with their national agencies, (meteorological) institutes, universities, NGOs, banks and insurers, private and public interest groups or representatives from vulnerable sectors. The involvement of the scientific community also allows to build on existing projects or assessments like in the case of the Austrian NAS (Kronberger-Kießwetter, Balas and Prutsch, 2017).

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Depending on a top-down or bottom-up approach of the plans and strategies, a more or less strong involvement of municipalities and provincialities is given, thus encountering the question of hierarchy. Ireland (Irish Department of Communications, Climate Action and Environment, 2018) and Estonia (Republic of Estonia, 2017) foster an explicit top-down led strategy. The NAS of Estonia relies on this strategy as "the regional and local level of Estonia are not sufficiently aware of the effects of climate change" (Republic of Estonia, 2017, p. 6). Other countries apply a combined top-down and bottom-up led approach as scientific literature and trends in climate risk suggest (e.g. Butler *et al.*, 2015). A common proceeding is the centralized definition of guidelines on a national level with input and implementation on the regional and local level.

Box 11. Linking top-down and bottom-up perspectives.

Good practice example for the linkage of top-down and bottom-up approaches

The Danish (Government of Denmark, 2012), Dutch (Dutch Ministry of Infrastructure and Water Management, 2018) and Swiss (Swiss Confederation, 2020) NAP apply a strong municipal or regional approach. Especially the Danish NAP is a good example for top-down guidelines with regional execution.

Principles

Just like for the governance, the indicated principles in the reviewed documents apply for the adaptation plans and strategies and not explicitly for *risk* or *risk assessments*. However, for the same reason as in the previous section, adaptation principles can have similar relevance for a risk context. While some documents do not mention any principles on which the adaptation strategy or plan orientates, most documents do implicitly include them – only few explicitly refer to such. Among the most mentioned, the **precautionary principle** prevails (e.g.(Norwegian Ministry of Climate and Environment, 2012; Italian Ministry of Environment, 2015; Government of Germany, 2020). Anticipatory (e.g. Ministry of Agriculture and Forestry of Finland, 2005; Dale *et al.*, 2019), flexible and risk-based (e.g.Department of the Environment, Food & Rural Affairs of the United Kingdom, 2018; Dutch Ministry of Infrastructure and Water Management, 2018) as well as science-based principles (e.g.Norwegian Ministry of Climate and Environment, 2012; Italian Ministry of Environment, 2015) also occur. Throughout the various documents many references to sustainability, sustainable development and resilience are being made.

Box 12. Risk approach as principle for adaptation.

Good practice example for risk approach as principle

Among other principles, Switzerland explicitly refers to a risk approach as a guiding principle for the implementation of the adaptation strategy (Swiss Confederation, 2012).

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Coverage of sectors and groups

The reviewed documents cover a very broad spectrum of sectors likely to be impacted by climate change and thus require adaptation considerations. However, due to their interconnectedness it is difficult to categorize them. Overall, they cover natural systems, the economic system, and social systems (Box 14). Although many NAPs and NAS follow a sectoral approach, risk is not always explicitly considered in the respective sectors. However, again, as adaptation considerations are ideally based on a risk assessment, risk still plays an indirect role in the sectors.

Box 13. Sectors covered by NAPs and NAS.

Natural systems: Ecosystems, coasts, forests, biodiversity, protected areas, soil, special ecosystem cases (e.g. Alps), land use, horticulture, agriculture & livestock, fishery, water, recreational use.

Economic systems: Business, industry, insurance & financial services, tourism, reindeer husbandry, insurance & financial services, IT & telecommunications, energy, food production.

Social systems: Health, society & welfare, migration, communication, education, natural & cultural capital, cities & urban environment, buildings, housing, spatial planning, infrastructure, transport.

3.3.2. Risk considerations in the Sendai Mid-Term Reviews

In this second part, the Sendai Framework Mid-Term reviews (MTR) is analyzed by focusing on the question: How comprehensively is *risk* being treated in the documents? For this, risk governance *(state actors & stakeholders, risk coordination & responsibility, top-down and bottom-up action, legal basis)* and countries' considerations and assessment of (climate) risk will be investigated. As the reviews mention many encountered problems and possibilities for improvement, risk-related issues regarding these will also be included.

As the reports were voluntary, only five EU-member countries submitted a national review: Austria, Belgium, Poland, Slovenia and Sweden. As Norway's and Switzerland's Adaptation Strategies and Plan were covered in the previous part, their MTR will also be included in this subsection.

The UNDRR provided guiding questions for the countries' MTRs which had an influence on the reports. Nevertheless, the reviewed documents do not show homogeneity. While the Belgian and Norwegian MTRs mainly provide direct answers to these questions, the Austrian and Polish reports build around these. All reports, except for Norway, include a retrospective and prospective view regarding risk, risk management or disaster risk reduction in their respective country.

The submitted MTRs do not explicitly take into account climate risk assessments but generally refer to national risk assessments, thus partially covering "anthropogenic" (Janowczyk and Królikowska, 2022) or "man-made" (Crisiscentrum Belgium, 2022) risks like social issues, the Covid-19 pandemic, the Ukraine war or technological, chemical and nuclear risks. However, climate change acts as a main risk driver according to the documents and thus will be the risk-related focus of this analysis.

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Governance aspects

Although NAPs/NAS and Sendai MTRs cannot be compared, overall, the MTRs provide more detailed insight about the ground level of risk assessment and management as more information about involved state actors and stakeholders is presented.

The respective state actors mentioned for risk governance responsibility vary from governmental control (e.g. Government of Austria, 2022) to specified ministries (e.g. Republic of Slovenia, 2016) or inclusion of governance actors on all levels from national to local (e.g. Swedish Civil Contingencies Agency, 2022). All MTRs refer to state agencies or directorates involved in risk governance and management like the Swedish Contingencies Agency (MSB), the Norwegian Directorate for Civil Protection (DSB) or the National Crisis Center in Belgium. Stakeholder involvement in MTRs is less pronounced than in NAPs or NAS, however strong intentions for more collaboration between governance actors and research is communicated (Republic of Slovenia, 2016; Government of Austria, 2022; Janowczyk and Królikowska, 2022; Swedish Civil Contingencies Agency, 2022).

While this perspective proposes a *top-down* led risk governance, the practical context of the MTRs and disaster risk reduction (DRR) allows a better conceptualization of the peripheral involvement of actors. All countries refer to the important role of the decentralized *bottom-up* DRR and civil protection. The Austrian MTR (Government of Austria, 2022) explicitly states that there are different competences on different levels according to the subsidiarity principle. This leads to a top-down and bottom-up cross-interaction with civil protection at the local level (e.g. Swedish Civil Contingencies Agency, 2022). Generally, all countries refer to the important role of the local or municipal level with e.g. a focus on risk and vulnerability assessments in municipalities (Government of Norway, 2022) or risk awareness campaigns on all four – national, regional, provincial and local – levels (Crisiscentrum Belgium, 2022). This decentralized and often voluntary based (e.g. Government of Austria, 2022) crisis management provides an optimal basis for response. However, not only local risk preparedness but also a climate risk understanding on all levels and for all actors is crucial for climate adaptation (see Table 6 about encountered problems).

The third point concerning risk governance refers to the *legal basis* of risk in the countries which submitted a Sendai MTR. All countries, except for Sweden's MTR, refer to the strong driving force of the European Union Civil Protection Mechanism (UCPM), which, among other, foresees the conduction of national risk assessments every three years. While some documents mention existing directives and decrees already regulating risk governance (Swedish Civil Contingencies Agency, 2022), all countries except for Switzerland agree on a missing legal basis or a need for improvement of the legal framework. Switzerland's MTR mentions an already existing and strong risk governance which is "built on a sound legal framework, strategies, clearly defined roles and functions across the administrative levels and sectors and adequate funding mechanisms" (Schmid, 2022, p. 15).

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Risk considerations and assessments

The key elements of climate risk – hazard, exposure and vulnerability – are only slightly touched upon in the MTRs. Hazard remains the most prominent driver of risk and is an important factor for risk assessment through e.g. hazard mapping (Crisiscentrum Belgium, 2022; Government of Austria, 2022; Janowczyk and Królikowska, 2022; Swedish Civil Contingencies Agency, 2022). Switzerland flags this as a remaining problem for risk assessments in the country (Schmid, 2022). Especially risk from flooding is emphasized (Republic of Slovenia, 2016; Crisiscentrum Belgium, 2022). Also, the Austrian, Belgian and Swiss MTRs proposed the consideration of multi-hazard risk, and at the same time acknowledge that residual risks will remain through climate change. Norway explicitly states that “reducing exposure to all of them [hazards] is not possible” (Government of Norway, 2022, p. 7), be it present or future (climate) risks. Interestingly, the MTRs of Austria and Poland (Government of Austria, 2022; Janowczyk and Królikowska, 2022) suggest the concept of “risk ownership” which links to possible solutions to responsibility issues.

Table 6. Encountered problems in Sendai MTRs.

Country	Encountered Problems
Austria	Legal framework, interconnectedness and collaboration with stakeholder, data improvement and mapping, inclusion of vulnerable and marginalized groups, awareness and acceptance of prevention actions
Belgium	Conceptual approach (risk-based, holistic) missing; North-South gradient
Norway	Clearer responsibilities needed, better hazard/risk mapping
Poland	Financing as key obstacle, lack of competence and knowledge, lack of guidelines for cooperation with research, lack of national strategy, reorganization of governance as constraint
Slovenia	Understanding risk and complexity, knowledge needed about how to analyze and assess risks
Sweden	Varying quality of risk assessments (national vs. local level)
Switzerland	Risk assessments mainly focus on hazards, lack of social vulnerability assessment, interconnectedness of risks, whole-of-society approach, gender equality, awareness

National risk assessments are the foundation for national emergency planning (e.g. Crisiscentrum Belgium, 2022), however the MTRs are often not explicitly climate risk-centered. Risk and vulnerability assessments form a basis for national emergency planning (e.g. Crisiscentrum Belgium, 2022) or civil protection (Government of Norway, 2022). In Sweden all government agencies, regions and municipalities need to prepare risk and vulnerability assessments (Swedish Civil Contingencies Agency, 2022). However, it is unclear to what extent these are climate related. Just like for the legal risk basis, countries are aware of the need for improvement regarding risk assessments; this concerns e.g. better guidelines (Swedish Civil Contingencies Agency, 2022) or a more systematic approach (Government of Austria, 2022). To support this by contributing to quantitative risk analyses, the establishment of a national database platform CESARE is planned in Austria (ibid.).

Encountered problems and outlook

The documents show a very heterogenous picture of encountered problems, which sometimes are country-specific (Table 6). However, some are generic: all MTRs agree to a varying

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extent that it still remains a **challenge to connect risk governance at higher levels with lower, more practically oriented levels**. This distribution of risk (incl. risk transfer) also strongly concerns the issue of unclear responsibilities as mentioned by Norway (e.g. Government of Norway, 2022).

3.3.3. Synthesis

The review of the documents shows how closely interconnected adaptation considerations, DRR and risk assessments are in the practical context. Especially the analysis of adaptation strategies and plans leads to mixed conclusions. In most documents risk is not well conceptualized, plays a rather shallow role with an often inconsistent use of risk language. Only few documents explicitly refer to CRAs as basis for their NAP or NAS. Some documents show good practice examples – if risk is emphasised, it usually coincides with a high level of risk conceptualization throughout the whole document. If that is the case, also, a generally more scientific based approach is utilized. On the other hand, the Sendai MTRs are more explicitly risk-oriented than NAPs and NAS with a broader risk consideration beyond climate risk. An overview of the main findings, problems and remaining gaps of this section is provided in Table 7.

The NAPs/NAS and Sendai MTRs show that the practical implementation clearly limps behind the scientific developments. Thus, the first step for an improved coherence across countries and regions needs to rely on a basic, generally accepted approach as part of a shared, inclusive and harmonic framework. Too many layers of complexity (e.g. multi-hazard or cross-sectoral considerations, inclusion of impact pathways) may discourage regions and stakeholders. Thus, according to the findings of this review, the most important step entails the provision of a clear risk conceptualization and related terms together with concise guidelines for climate risk assessment. Also, what most reviewed documents had in common, was the lack of robust data or the knowledge about its proper usage. A local/regional approach is already prevalent according to many documents, thus pointing into the right direction. However, especially at this spatial level, knowledge transfer must be guaranteed.

Table 7. Overview of the main findings in 3.3. Risk assessments for national and international policy dialogue.

Category	Summary
Risk considerations	Overall **sectoral risk considerations** according to relevant hazards (natural, economic, social systems). Only few documents show concise risk conceptualization and/or proper use of risk language according to IPCC AR5.
Risk governance	Mainly led by state actors (government or ministries) and state agencies or directorates (*top-down*) with involvement of academia, stakeholder groups and NGO's. Strong focus

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	on involvement of regional, municipal and local level (*bottom-up*). Especially for DRR an emphasis on peripheral and decentralized civil protection.
Principles	Only few countries explicitly refer to principles in their documents. While the **precautionary principle** prevails, anticipatory, flexible and risk-based as well as science-based principles are also being mentioned.
Hazard x vulnerability x exposure	**Hazards** considered as the **main risk driver** with some references of hazard maps. Exposure and vulnerability aspects often neglected. References to exposure/vulnerability assessments/maps rare.
Technical implementation choices	**Climate scenarios** mainly orientating on IPCC scenarios with 2100 as horizon. However, this differs for adaptation considerations in the respective countries with short-, medium-, and long-term time frames for adaptation measures. Mainly direct and indirect **impact chains** addressed in the documents with systemic, cross-sectoral, cascading and cumulative risk mentioned.
Risk aspects of adaptation	Adaptation considerations indirectly allow insights in risk-driven practical implementations such as nature based solutions, mitigation-adaptation synergies or a circular economy. Also, maladaptation is superficially addressed.
Social impacts	Broadly considered with trend towards more inclusion of social aspects of climate change in recent documents.
Remaining gaps and problems encountered	Data availability and processing; missing legal framework; better guidelines and improvement of risk assessments; more systematic and conceptual approach needed; financing; more inclusion of social aspects in climate risk; interconnectedness of risks.

4. Conclusions

By reviewing relevant national or regional documents and peer-reviewed literature on climate risk assessments this deliverable provided an overview of the state of the art, trends and drawbacks in this further developing field, thus setting a stable basis for the CLIMAAX framework and toolbox development. The deliverable provides good practice examples, emerging concepts as well as limitations and remaining gaps to further inform CRA framework in WP1.

4.1. State-of-the-art

The conceptual evolution – from climate vulnerability to climate risk – has been proceeding in the last decade and is of crucial importance. IPCC and international standards presented key general

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take-aways with regard to the **state of the art in theory and general practice** when carrying out CRAs to support adaptation planning and reporting at a regional scale.

Various risk assessment frameworks have been developed. Mostly, these frameworks suggest to integrate CRA with assessments of current and future risk management or adaptation options to support decision-making. Generally, such frameworks follow a cyclical and iterative process from risk assessment to supporting risk management. Lately, the literature has been emphasizing to start with a clear system definition (ideally current and future) and respective stakeholders to be involved, before proceeding with actual risk estimation.

The development of CRAs in the scientific community has unveiled several important considerations and advancements towards a deeper understanding of the complex nature of climate risks.

CRA literature has strongly focused on conceptualizing, assessing, modelling and quantifying the **hazard** component. Different classification of hazard typology in the literature has allowed for a comprehensive assessment of various hazards and their impacts. Additionally, CRAs are shifting towards a **multi-hazard-risk perspective** by considering the dynamic nature of risks, their interactions, and the combined effects of multiple hazards.

Exposure, a key aspect for CRAs, has been recognized as a **dynamic concept**, which has been examined from two angles: as a variable dependent on the geographical location, and as a variable dependent on the changing hazard characteristics resulting from climate change. By incorporating both angles, CRAs provide a more nuanced understanding of the potential risks that different elements (i.e., including subpopulations, assets, infrastructure, socioeconomic activities, sectors and environmental resources and processes) face in varying contexts.

Vulnerability, another crucial element in CRAs, including sensitivity and adaptive capacity elements, is also dynamic, exhibiting variations over time as a reflection of societal evolution, and with different conceptual forms: physical, social, and ecological. While sensitivity consists of natural factors, management aspects, and societal characteristics, adaptive capacity encompasses economic, governance, knowledge, and available adaptation options. Despite both vulnerability and adaptive capacity are critical in influencing the overall risk profile, these aspects are still not well integrated in the assessment of climate risks.

More recently, CRA literature also emphasizes the importance of considering climate change **responses** as potential sources of risk. Effective climate responses are influenced by various factors, including normative choices, political realities, risk perception, heuristics, and behavioral dynamics. Moreover, the evaluation and simulation of climate responses have helped progress in understand-

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ing risk-increasing factors, maladaptive effects, adaptation limits, and residual risks. Recognizing responses as a risk component and these other factors has provided valuable insights for improving future CRAs.

Statistical, economic, and financial evaluation of climate change **impacts** has broadened not only the understanding of the multifaceted effects of climate risks across different administrative, geographical, sectoral, and governance boundaries but has also bridged interaction between disciplines by considering, for example, losses of well-being and effects on human health. Advancements in Earth observation, GIS, and remote sensing techniques have contributed to providing accurate and timely data for evaluating and modelling impacts, and, thus, assessing climate risks more precisely.

Uncertainty in CRAs strongly emerges from the non-stationary nature of climate change and remains a big issue for decision-making. To overcome this, researchers have employed various approaches, including enhancing and integrating models, utilizing localized and high-quality data, promoting collaboration between disciplines, and exploring different probabilistic functions. In recent years, Machine learning techniques, such as decision trees, random decision forests, and artificial neural networks, have also been integrated into risk assessments to reduce uncertainty and incorporate complexity, and it is seen as a promising technology to improve the next generation of CRAs. Thus, **managing uncertainty** instead of reducing it seems to be the way to move forward in CRAs. This can be done by employing a variety of climate scenarios, socio-economic futures or by using event-based storylines and their resulting impacts which can be combined with probabilistic approaches. This way, robust and adaptive adaptation options can be formulated. **This means instead of optimising for a certain future, adaptation is optimised for a multiplicity of futures.**

Finally, the **involvement of local stakeholders** has gained **traction** as a crucial aspect of CRAs, considering that incorporating local knowledge and perspectives can have two-fold benefits: provide a deeper understanding of the local contexts and hidden aspects of risks that models cannot capture, and build a shared understanding of the problem at hand—particularly important for better decision-making processes. Consequently, bottom-up approaches have obtained momentum within the CRA field, and have been increasingly utilized as a means to complement top-down approaches.

4.2. Beyond state-of-the-art: gaps that need further addressing in practice and science

The national and regional documents (i.e., UCPM risk assessments, Sendai Mid-Term reviews, National Adaptation Plans and Strategies) gave an overview of the widely differing risk landscape in the respective countries with overall similar problems and gaps remaining. Additionally, the peer-reviewed literature encountered and discussed remaining issues and opportunities for improvement in the CRA field (see sections 3.1.3 and 3.1.4). Table 8 summarizes the most prominent prevailing practical and conceptual gaps.

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Table 8. Practical and conceptual gaps in the assessment of climate risks.

Conceptual gaps emerging from the scientific literature	Practical gaps encountered in national/regional documents
○ Adopting a **multi-risk framing**, integrating multiple hazards and the dynamic nature of risks (interacting, cascading and compounding risks). ○ Assessment of **exposure** and **vulnerability dynamics** coupled with future socioeconomic changes and adaptation pathways. ○ Integration of various **vulnerability forms** (physical, economic, social, ecological) and indicators for **sensitivity**, coping and **adaptive capacity** ○ Inclusion of **societal dimensions of risks** (e.g., behavior dynamics, normative choices, political realities, social ties, risk perception, disparity and tolerance). ○ Analysis of **systemic, transboundary, and cross-sectoral risks,** including risk transmission mechanisms, impact aggregation, feedback loops. ○ Identification of influential variables or processes **amplifying risks**. ○ Quantification of **residual risks**, adaptation limits, tipping points, **time of emergence** and hazard **threshold values**. ○ Further improvement in **uncertainty** assessment methods and evaluation of **confidence** levels. ○ Options for **managing uncertainty** e.g., by combining probabilistic approaches with event-based storylines. ○ Assess probabilities of future events in **transient** climate conditions. ○ Need for embracing principles of **social justice**, **equity, transparency, plurality**, adaptive management and systems thinking. ○ Integration of parameters and indicators of **system stability** and resilience.	○ **Harmonized risk approach**: Diverse risk approaches with differing levels of development in documents. ○ Shared **risk conceptualization** broadly missing. ○ Risk assessments need to shift focus towards more integration of a **climate change perspective**. ○ Missing **guidelines** for systematic and conceptual approach of CRAs or lack of knowledge and competence for application of guidelines. ○ Explicit inclusion of **vulnerability** and **exposure** as part of the risk concept beyond a hazard-only focus. ○ **Social aspects** (vulnerability & exposure) of climate risk (e.g. unequal exposure of socio-economic and demographic groups, psychological stress or gender) not included or remain superficial. ○ Linkage of **bottom-up** and **top-down** approaches with clear risk responsibility. ○ **Legal** framework for risk governance and management. ○ **Data** availability and processing ○ Understanding and/or assessing **complexity of risk** (interconnected systemic risk, compound and cascading risk, impact chains).

Overall, findings in the CRA literature point out the need for a **comprehensive and adaptable framework** that considers the complexities and uncertainties associated with climate-related risks across scales, while calling for a better involvement of local stakeholders, linkage of top-down and bottom-up approaches, and new forms of engagement. Moreover, innovative techniques such as machine learning and hybridization of probabilistic models seem to be promising alternatives for reducing uncertainty and capturing the dynamic nature of risks better in future CRAs. Furthermore, providing an overview of the various CRA tools to be employed, describing advantages, limitations, drawbacks,

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pre-conditions and requirements will be essential to help technical analysts efficiently assess climate risks and help decision-makers interpret and communicate the results effectively. Nevertheless, for CRA to advance towards more accurate and reliable results, the **availability of and access to data for quantitative analysis at lower decision-making scales** remains an imperative challenge to overcome.

A shared conceptualization of climate risk through a harmonized framework in combination with a comprehensive CRA is therefore crucial to address present and future challenges emerging from climate change. The regional approach of the CLIMAAX project will allow the transfer of state-of-the-art risk conceptualization and practice through an applied tool to the ground-level, thus embracing the knowledge of regional and local specificities.

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