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Integrated risk analyses as part of national climate risk assessments: lessons learnt from the climate risk assessment of Germany

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Abstract

Purpose – Climate risk assessments (CRAs) become more and more necessary to prepare and prioritise adaptation action. On a policy level, the results of CRAs offer the foundation for national adaptation strategies. However, existing CRAs oftentimes do not exploit their full potential by means of an integrated assessment, i.e. to illustrate the complexity of cascading risks, provide cross-sectoral results, integrate adaptive capacity and demonstrate spatial patterns. This paper seeks to fill this gap by dissecting integrated assessment approaches of national CRAs.

Erratum: It has come to the attention of the publisher that the article, Kahlenborn, W., Voss, M., Porst, L., Zebisch, M., Renner, K. and Schauser, I. (2025), "Integrated risk analyses as part of national climate risk assessments: lessons learnt from the climate risk assessment of Germany", *International Journal of Climate Change Strategies and Management*, Vol. 17 No. 1, pp. 68-88. https://doi.org/10.1108/IJCCSM-10-2023-0128 incorrectly listed the affiliation of Maike Voss as GIZ, Ouagadougou, Burkina Faso, this has now been corrected to GIZ, Eschborn, Germany. The publisher sincerely apologises for this error and for any inconvenience caused.

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Design/methodology/approach – The paper focuses on the integrated analyses of the results of CRAs. Based on a review of selected national, multi-sectoral CRAs, the authors explore the application of such analyses. Additionally, drawing on the latest climate impact and risk assessment for Germany, the authors highlight latest approaches and their implications.

Findings – The authors show that even though progress in establishing integrated assessment methods has been made, no common framework exists so far and only few national CRAs include extensive integrated analyses. Nevertheless, the German example demonstrates that integrated analyses can provide a comprehensive overview over risk dynamics, (spatial) patterns and needs for action thus providing practical advice for decision-making on a national adaptation policy level.

Originality/value – While it is common knowledge that CRAs in general provide better results, if the models applied are integrated (i.e. combining climate, geo-physical, economic, etc. factors), little attention has been given to the integrated analyses of their results. This paper provides valuable new insight on this aspect which will become far more important in the future.

Keywords Adaptive capacity, Climate risk assessment, Integrated analysis, Cross-sector risks, German CRA 2021

Paper type Research paper

1. Introduction

The European Environment Agency (EEA) reported that since 2018, 14 European countries have released new climate risk assessments (CRAs). These countries include Austria, Belgium, Denmark, Finland, France, Hungary, Ireland, Romania, Slovenia, Spain, Italy, Switzerland, Germany and the Czech Republic (EEA, 2022). Despite the considerable activity in this field, the existing CRAs have been criticized extensively in the literature (Adger *et al.*, 2018; Arribas *et al.*, 2022; Bednar-Friedl *et al.*, 2022; EEA, 2022; Ford *et al.*, 2018; Harrison *et al.*, 2016). One major criticism is that CRAs often fail to adequately consider non-climatic factors, such as socio-economic developments, and how they interact with climatic factors. Additionally, they often overlook transboundary and international climate risks, e.g. those associated with supply chains. Another limitation of CRAs is that they do not consider the dynamic interactions that occur across different spatial scales (e.g. at the national and local levels). Social equity in the context of climate-change impact and the amplification of risks due to societal preferences are often neglected. Furthermore, the links between CRAs and national risk assessments in the context of disaster risk management (Sendai framework for disaster risk reduction) have not been fully addressed.

To address these criticisms, CRAs use integrated models that combine climatic and non-climatic factors, particularly socioeconomic factors, and to some extent, incorporate dynamic interactions. Depending on their complexity, they evaluate the climate impacts on physical, ecological, economic, social, cultural and institutional systems and consider the interactions between these systems. However, even these improved and integrated climate risk models do not necessarily meet the needs/goals of policymakers. From the perspective of policymakers, CRAs should not only help identify the potential impacts of climate change on specific systems, sectors or regions and provide a better understanding of the uncertainties and risks associated with climate change, but also serve as a basis for developing adaptation strategies that can reduce the vulnerability to these impacts (Weaver *et al.*, 2017). Notably, CRA results should enable policymakers to prioritize actions and allocate funding effectively. To obtain the information necessary to address these questions, it is important to conduct intersectoral comparisons, identity the regional hotspots, understand the cascading impacts and consider the adaptive capacity.

Even with a comprehensive and integrated CRA model that considers a wide range of factors, the absence of an integrated analysis of model results limits the provision of necessary information; several scholars have acknowledged this issue. Harrison *et al.* (2016) and Ford et al. (2018) indicated that CRAs should account for feedback loops and interactions among non-climatic factors and adopt cross-sectoral approaches, to adequately assess complex climate-change risks. It has also been argued that CRAs should be linked more systematically and closely to the development of action plans, to ensure informed decision-making, particularly with respect to policymaking (EEA, 2022; Ford *et al.*, 2018). Arribas *et al.* (2022) highlighted the inadequacy of conventional sectoral risk assessments in capturing the complexity of the cascading risks associated with climate change and their interconnections.

To address these challenges and meet the expectations of policymakers, CRAs are incorporating additional elements that can support sophisticated and detailed integrative assessments. In the context of this article, when talking about "integrated analysis" or "integrated assessment" we focus on such additional integrated elements of assessments. Based on our experience, we focused on the following four facets that were considered the most relevant for linking CRAs to climate-adaptation policymaking:

(1) Comparing risks across sectors, using standardized criteria;
(2) Examining the cascading impacts and risks across different systems and sectors that may result in significant compound risks and identifying the thematic clusters of interconnected impacts and risks;
(3) Identifying spatial hotspots affected by multiple climate drivers, impacts and risks; and
(4) Integrating the aspects related to adaptation and adaptive capacity into the CRA.

The objective of this study is to examine the different approaches of integrated assessments used by national CRAs and their outcomes. This study compares national-level, multisectoral CRAs, focusing on their integrated assessment approaches. Furthermore, it presents the approaches used for an integrated risk assessment in the latest climate impact and risk assessment for Germany, and discusses the lessons learned that may be relevant for the risk assessment for other countries. Finally, we present the major conclusions of our study and provide suggestions for conducting integrated analyses of future national CRAs.

2. Methods used for integrated analyses: comparison of selected national climate risk assessments

Post the mid-2000s, national-level CRAs have gained momentum, with some incorporating integrated analyses (Ford *et al.*, 2018). In an effort to advance research in this area, we conducted a comparative analysis of the methodological approaches to integrated analyses in national-level CRAs.

This review focuses on multisectoral national-level CRAs conducted over the past 15 years, with the reports being available in English or German. Drawing on our methodological expertise in conducting the last two CRAs for Germany, we specifically examined the CRAs conducted for countries with characteristics similar to Germany, in terms of climate vulnerability, adaptation planning and action scopes. The review encompasses five national-level CRAs of Europe and North America.

To evaluate the CRAs, we considered the following criteria:

- Were different risks assessed in an integrated manner? Were the risks compared, and if so, what criteria were used for comparison? To what extent were diverse climate risks integrated and at what scales?
- Did the CRA consider the interactions between different climate impacts, especially across sectors? Did the assessment reveal cascade effects? Did it consider such effects as part of case studies or as part of a systematic overall analysis?

- Did the CRA include an analysis of the spatial characteristics of climate change? Does the assessment contain a graphical illustration (map) that indicates the hotspots (areas of increased climate stress) based on climate indicators or based on the spatial analysis of climate impacts?
- Did the CRA analyze the adaptive capacity? Does the CRA reflect the results of the analysis of adaptative capacity in its assessment of climate risks?

By applying these criteria, we thoroughly examined the integrated approaches used by the selected national-level CRAs. Table 1, at the end of the article lists the review results, along with the central methodological features of all the CRAs.

With respect to multisectoral CRAs at the national level, only a few studies present detailed integrated analyses. The review reveals different approaches. In most cases, this part of the CRA was included non-explicitly and less comprehensively than other sections of the CRAS's final report, which constitute stand-alone chapters. The only exceptions to this pattern were the studies on Switzerland and the UK. In both cases, a comprehensive integrated analysis was conducted.

Overall, the comparison of the selected CRAs illustrates the varying degrees of sophistication regarding the methods applied to systematically assess climate risks in an integrated manner. In most cases, qualitative methods were applied and external experts, scientists and stakeholders consulted to validate the methodological approach to the integrated assessment.

Partially, cross-cutting themes are formulated or region-based perspectives regroup and integrate risks identified and evaluated before. At times, integrated assessments also address cross-sectoral interaction of climate risks. However, exploring interdependencies of climate risks across sectors as well as cascading effects – although central features of climate change – does not seem to be part of the standard procedure of multi-sectoral national-level CRAs.

In contrast, risk rankings with relative risk values are rather common in CRAs and serve as a basic version of an integrated assessment, i.e. in a comparative manner. The range of values is limited, though. Specifically, the CRA comparison has shown analogue ranges of risk scores – high, medium, low – and therefore seemingly similar conclusions from the CRA results can be drawn, i.e. which needs for action and priorities are identified eventually informing policies. However, these scores (high, medium, low) differ regarding the specificity and scope of their input parameters and thus regarding the information they provide, which affects the comparability of individual climate risks, also across sectors or areas.

Spatial patterns of climate risks usually are not addressed. Even less is there a particular interest in aggregating patterns of risks. None of the CRAs in our sample contains a hotspot analysis. That, obviously, hampers conclusions for particular regions which are differently impacted by climate change. Nevertheless, several CRAs try to distinguish in the assessment to some extent between different regions.

Policy recommendations derived from the CRA results are a common element of the CRA in our sample, indicating an integrative perspective on the analytical results, which are therefore transferred to an aggregated level. As this CRA comparative analysis has shown, such recommendations for adaptation action to be taken as core results of a CRA on an aggregated level tend to be more specific the more comprehensively and profoundly the sector-wise assessment results have been analyzed in an integrated manner. By assessing specific risks with and without adaptation, and by analyzing adaptive capacity and including that in the risk assessment, estimations of future challenges and current urgency of action are becoming more meaningful for climate adaption policy formulation.

Overall, our review indicates that the development of effective methods for the integrated assessment of climate risks is an ongoing endeavor. To date, a generic approach to analyze

Table 1. Review of the multisectoral, national-level climate risk assessments (CRAs) considered in this work, while focusing on integrated analysis

Country	Central methodological features of CRA	Integrated analysis approach	Type of results derived from integrated analysis
Canada [Council of Canadian Academies (CCA), 2019]	Based on a literature study and an expert workshop, 12 major areas at risk from climate change were identified, with more than 60 individual risks The risk assessment was based on the expected consequences and their likelihood of occurrence over the following 20 years Consequences and likelihood were rated on a scale of 0–100 Five main criteria for assessing the relative consequences of the climate-related risks were taken into consideration: (i) Impacts on the environment and natural systems; (ii) Impacts on the economy; (iii) Impacts on society and culture; (iv) Impacts on human health and wellness; and (v) Impacts on geopolitical dynamics and governance	Applying the five main criteria, the assessment provides a cross-sectoral risk evaluation The discussions of the consequences of climate-change risks were informed by the consideration of potential impacts across multiple domains. Thus, cascading effects were recognized but not systematically analyzed The assessment did not include a hotspot analysis Adaptation potential was assessed for the 12 areas of climate risk (included in the risk assessment). This assessment took into account both current conditions and anticipated autonomous or planned adaptation	Based on the results of the analysis per area, the six most-affected areas were determined by the expert panel, in view of each areas' significance on a national scale The results provide policymakers an overview on the relative likelihood and consequences for major areas of climate change risk Possible actions were derived and structured in three categories: coordination and collaboration, capacity building and assets and operations The assessment demonstrated that all 12 areas of risk can be meaningfully reduced through adaptation measures that address vulnerability or exposure
Ireland (Flood *et al.*, 2020)	The assessment identified nine key sectors for analysis. The nine sectors were then grouped into four cross-sectoral themes: a) natural and cultural capital, b) critical infrastructure, c) water resources and flood risk management and d) public health Risks were not calculated in a standardized way, nor did the assessment use impact categories; time frames were not specified The assessment applied a three-tiered CRA	The assessment did not apply specific methodological approaches for cross-sectoral comparisons, but comparison was facilitated through the four cross-sectoral themes The themes were cross-cutting in nature and were also applied to encourage the identification of interdependencies across sectors and government departments Part of the assessment (chapter on general considerations) was evaluating adaptation	The results of the risk assessment were displayed across the four cross-sectoral themes by highlighting climate-change-driven risks and opportunities With one of the key elements of Ireland's CRA being stakeholder engagement and stakeholder workshops, its assessment was comparably qualitative The key results from the approach, which were used to inform policymakers consisted of a

(*continued*)

Table 1. Continued

Country	Central methodological features of CRA	Integrated analysis approach	Type of results derived from integrated analysis
	framework: First tier (capturing the range of risks posed by climate change): based on a literature review and stakeholder consultation. Second tier: assessment included literature review and expert input to identify climate risks of national importance Third tier: detailed assessment, i.e. case-study examples for assessing priority climate risks	options and considering adaptation pathways. Also, adaptation options were considered in the discussion on the impacts in the four cross-sectoral themes The assessment does not look into the spatial distribution of climate risks	summary overview assessment of climate-change risks across the identified themes and the recommendations for future adaptation activities
Netherlands (Ligtvoet *et al.*, 2015)	The Netherlands assessed the risks of climate change for 55 risks within nine areas. For each of these risks, impact and probability were considered. Probability was indicated as more often, similar, or less often relating to the frequency of already occurring events. The magnitude was assessed related to three impact categories: a) economic risk (projected damages in Euro), b) human risk (deaths/casualties), and c) nature and environmental risks (impact on local, regional or national scale and degree of irreversibility) For the risk assessment, the current spatial layout and size and composition of the Dutch population was assumed and then, combined with climate-change projections for 2050 An estimation of the impact was applied with the baseline scenario "in case of no adaptation action"	By applying standardized thresholds for each impact category, the assessment does allow for cross-sectoral comparability. In fact, it is a specific objective of the assessment to provide a national overview on the size and likelihood of climate risks across a broad area of topics The assessment is specifically meant to gather information on climate effects and to provide entry points for the adaptation strategy. In doing so, adaptation measures are addressed, but they are not included in the risk assessment Also, the assessment does not map the climate risks or identifies hotspots, though it does differentiate for certain risks (between local-, regional- and national-level risks)	The semi-quantitative scoring provides policymakers an overview of the estimated damages/impacts and their likelihood within each risk dimension (economic, human, nature and environmental risks) within the chosen time-span. However, no cascading effects are included. While this type of assessment gives a structured view on the climate-related risks for the economy, citizens and environment, it does not allow for a detailed analysis and quantification of the interactions between the risks

(*continued*)

Table 1. Continued

Country	Central methodological features of CRA	Integrated analysis approach	Type of results derived from integrated analysis
Switzerland [Bundesamt für Umwelt (BAFU), 2017]	About 50 risks are covered by the Swiss CRA, mostly qualitatively and in some cases, also quantitatively Risk is perceived as a combination of likelihood and damage Thresholds have been applied where possible The assessment differentiates between three levels of risk increase (small, moderate and significant) The risk assessment compares the current state with the situation in 2060, without applying adaptation measures The synthesis of climate-related risks and chances was based on eight case studies (carried out in different areas of Switzerland), a literature review, and expert judgements: – Risks and chances were partially derived from case studies and complemented by a set of risks identified by literature review and expert judgement – Quantitative and qualitative assessments of risks and chances stated in the case studies were aggregated to the regional level	Switzerland applied a cross-sectoral, integrated, and data-driven approach to analyze the climate-related risks Contrary to the case studies which followed a sector-specific focus, the synthesis grouped the results in a cross-sector approach, while focusing on different types of challenges The method of all case studies and thus the basis of the assessment follows a standardized approach. Differences in the implementation of the method in the local case studies were later addressed and corrected Adaptive capacity was evaluated for six different categories (knowledge, motivation, legal structure, technologies, finances and institutional structure), while applying three levels of parameter value. Individual adaptation measures were not considered in the assessment The assessment did not include a hotspot analysis. Neither did it include the cascading effects of the impacts	Identification of need for action and specific adaptation measures are not the primary content of the assessment However, the combination of a quantitative climate-risk assessment, with qualitative expert panels, allowed for the identification and prioritization of cross-sectoral climate-related risks in Switzerland. This forms the basis for determining adaptation activities at the federal level The results of the analysis are further used by the case-study regions to develop their own strategy and adaptation planning Where comparable framework conditions exist, results can be transferred to other spatial units and can be used for the concretization of further procedure for climate adaptation

(*continued*)

Table 1. Continued

Country	Central methodological features of CRA	Integrated analysis approach	Type of results derived from integrated analysis
United Kingdom (CCC, 2020; CCC, 2021; Watkiss and Betts, 2021)	Based on various inputs, the assessment identified and evaluated 61 risks and opportunities, grouped into five areas: Natural environment and natural assets; infrastructure; health, communities and the build environment; business and industry; and international dimensions The CRA project analyzed separately England, Wales, Northern Ireland and Scotland Projections were made for two different time horizons (2050 and 2080) The CRA distinguishes three levels of magnitude defined by standardized criteria, based mostly on qualitative assessments, and in a few cases, on quantitative assessments. It does not specify likelihoods for individual risks	The assessment allows for a cross-sectoral comparison of risks through standardized criteria and further validates individual risk assessments The analyses of adaptation were a major focus of the assessment. This included an analysis of current adaptation policies, non-governmental adaptation, adaptation gaps and barriers to adaptation Where an adaptation shortfall was identified (i.e. the risk had a residual high, medium, or unknown magnitude score), the final step of the assessment considered the potential benefits of additional adaptation, above what is currently happening or planned. This includes assessing possible additional adaptation action, the indicative costs and benefits of additional action and applying an overall urgency score The CRA includes a quantitative assessment of interacting risks between infrastructure, the built environment, and natural environment. For that purpose, network (or systems) maps portraying principal interactions within and between the sectors were developed The assessment differentiates between four areas, but does not contain standardized maps of risks or aggregate spatial patterns of hotspots	The analysis results were used to deduce eight priority areas for future adaptation policies Moreover, the priority areas for adaptation action were identified, which included: • Urgency degrees • Gaps in adaptation planning • Mainstream options for adaptation into current policies Also, the responses of adaptation policy to the interacting risks were identified

Source: Authors' own creation

and assess climate risks from a cross-sectoral perspective, to draw solid and sufficiently precise conclusions on an aggregated level, is not in place. In this regard, the Climate Impact and Risk Assessment 2021 (CRA2021) for Germany presents an important contribution. Hence, its approach and methods applied to assess climate risks in an integrated manner will be explained in the following section.

3. Climate impact and risk assessment for Germany

3.1 Point of departure

The approach applied in the Climate Impact and Risk Assessment Germany 2021 (CRA2021) is based on the methods and experiences from the two previous CRAs of Germany, the state-of-the-art in the fields of climate change research, climate risk concepts and definitions adopted by the Intergovernmental Panel of Climate Change (IPCC) as well as inspirations from other national CRAs [e.g. Bundesamt für Umwelt (BAFU), 2017; Warren *et al.*, 2017].

Notably, the CRA2021 is the third National Climate Risk Assessment conducted for Germany with the previous two assessments being conducted in 2005 and 2015. The "Climate Change in Germany – vulnerability and adaptation strategies of climate-sensitive systems" report was published in 2005. The approach in the 2005 study was sectoral and the concept was based on vulnerability, adaptation and capacity to adapt (Zebisch *et al.*, 2005). The analysis was to a large degree quantitative deriving the required information from socio-economic-, emission-, climate-, land use-, ecosystem- and impact models, supported by a literature review and expert consultations (Zebisch *et al.*, 2005).

In 2015, the Federal Environment Agency of Germany [Umweltbundesamt (UBA)] published the second assessment report, "Germany's vulnerability to Climate Change." The report presented a scientific analysis based on the collaboration of a network of experts who represented 16 federal authorities and institutes, referred to as the "vulnerability network." The trans- and inter-disciplinary expertise of an authoritative network was a key part of the vulnerability assessment (Buth *et al.*, 2015a). The concept of "impact chains," i.e. schematic visualizations of the cause–effect relationships between climatic drivers and potential impacts, represented the basic framework of the 2015 vulnerability assessment (Zebisch *et al.*, 2022). The overall framework of the assessment approach was the vulnerability concept of the Fourth Assessment Report (AR4) of the IPCC, which defines vulnerability as the "[…] degree to which a system is susceptible and unable to cope with adverse effects of climate change […]" [Intergovernmental Panel on Climate Change (IPCC), 2007; Buth *et al.*, 2015a]. The 2015 assessment report uses maps to present not only spatial patterns of indicators for climatic drivers, but also socio-economic developments as well as the severity of climate impacts for the three time periods analyzed for Germany (Buth *et al.*, 2015b).

The 2015 assessment analyzed the vulnerability to adverse effects of climate change in 14 sectors, by applying the same method, thereby allowing for a cross-sectoral comparison of climate risks. The assessment also included an initial analysis of the interdependencies between the various sectors, though not a sound analysis of cascading effects. In addition, the 2015 assessment involved a geographic assessment by assigning climate area types, based only climate signals – not on local vulnerabilities – delineating the specific challenges these areas meet in the future. Thus, the 2015 assessment already contained important features of an integrated analysis all bundled into one distinctive section of the CRA. Notably, the assessment did not cover adaptive capacity, even less a cross-sectoral appreciation of adaptive capacity even though this information is of high interest to policymakers.

3.2 Climate impact and risk assessment 2021 (CRA2021) for Germany: general risk-assessment approach

The methodological framework of CRA2021 for Germany involves two main aspects. The key underlying concept is the definition for climate risk determined by the IPCC Fifth Assessment Report (AR5), with its main components being "hazard," "exposure," and "vulnerability" [Intergovernmental Panel on Climate Change (IPCC), 2014]. In the report, the concept of climate risk is represented by "climate impact chains." The second important aspect of the methodology is combining scientific analysis with a normative process of evaluation (Kahlenborn *et al.*, 2021). The scientific analysis comprises a literature review, along with an analysis of indicators and model outputs and interviews of experts. The normative part was conducted in collaboration with the members of the network "Climate Change and Adaptation," a network of representatives from different sectoral federal agencies (Kahlenborn *et al.*, 2021). In addition to the members of this network, other experts also contributed to the analysis by providing data and knowledge. Moreover, the Interministerial Working Group on Adaptation (IMA-A) was consulted during the decision-making processes. Notably, normative decision-making and the co-development of the methods was an interdisciplinary process.

Future projections were represented by considering two cases: a "pessimistic" and an "optimistic" case. The "optimistic" case refers to a future climatic and socio-economic development with less adverse consequences of change than the "pessimistic" case. For climate projections, this means that for the majority of climate indicators, the 15th percentile of the representative concentration pathway (RCP8.5) was used to represent the "optimistic" case, and the 85th percentile of the ensemble of climate projections was used to represent the "pessimistic" case (Kahlenborn *et al.*, 2021). Note that the CRA2021 report covered three time periods: the present time period (1971–2000) and the middle (2031–2060) and end (2071–2100) of the 21st century. Kahlenborn *et al.* (2021) developed comparable maps for the different periods and cases.

Out of 102 climate risks for 13 action fields identified in a first step, a selection of the climate risks was analyzed in more detail. For each climate risk, we carried out literature review, data and model analyses, review of further information, elicitations (through expert workshops) and interviews. The analysis results were summarized in textual descriptions, cartographic maps and figures. Subsequently, the climate risk analysis per sector was subjected to a review process.

In a next step, the results of the analysis were used as the basis for risk evaluation. The members of the network of the federal agencies evaluated the climate risks (low, medium and high scales) for the three time periods. Similar to the approach used in the 2015 assessment, most experts evaluated across sectors, i.e. the evaluation was not confined to sector experts. Planned adaptation measures were excluded from the evaluations. The risk evaluation for the 2031–2060 time period was differentiated for the "optimistic" and "pessimistic" cases. The network members also evaluated the certainty of the available information, as well as the estimated time for implementing adaptation measures. The final score per climate risk was calculated using the Delphi method and various rounds of consultation (Kahlenborn *et al.*, 2021).

3.3 Integrated assessment: methodological approaches and challenges

The integrated analysis was a separate final procedural step of CRA2021. This resulted in a standalone report. In the integrated analysis, the results that were previously available at the climate impact chain specific or at the sectoral level were combined and evaluated in various ways. The most important evaluations involved the four integrated assessments at the center of this article:

- Comparing risks across sectors using standardized criteria.
- Examining cascading impacts and risks across different systems and sectors.
- Identifying spatial hotspots.
- Integrating aspects related to adaptation and adaptive capacity.

The respective approaches, using new or further developed methods compared with previous analyses, and the methodological challenges are discussed individually below.

3.3.1 Cross-sector comparison of climate risks. As described above, climate risks were assessed for each individual climate impact for the different time horizons and in case of a stronger or weaker climate change. In addition, we carried out a comparison of climate risks across fields of action (sectors) Figure 1. The assessments of climate risks for the individual climate impacts and for the fields of action were compiled in an overall view, as is done in other climate risk analyses (see the discussion in Chapter 2 of this article).

The evaluations within a single sector are generally easy to coordinate; this does not hold true for cross-sectoral evaluations. The lack of defined thresholds for assessing climate risks and the unavailability or inability to generate information that would substitute for such thresholds (e.g. precise quantification of monetary damages) for many climate impacts contribute to this challenge.

Within the CRA2021, various measures were taken to enhance cross-sector comparability. The research consortium provided an initial proposal to promote the comparability between sectors. The network process fostered a shared understanding of climate impacts. Many network partners participated in assessments across multiple sectors, facilitating cross-sector comparisons. Furthermore, the presentation, discussion and subsequent adjustments of the assessment results within the network contributed to the achievement of a significant level of comparability between different action fields.

Good cross-sectoral comparability was achieved using these methodological approaches. Notably, the resources and time required for implementing this approach are very high. This limitation should be considered by future CRAs that aim to follow a path similar to that of CRA2021.

3.3.2 Impact cascades. The integrated analysis included an assessment of the interactions among different climate impacts. The interlinks among the climate impacts demonstrate how different climate risks and sectors are influenced by each other. Thus, the cascading and reinforcing effects can be identified. The analysis was based on the assumption that the negative consequences of climate change on climate impacts also negatively influence other downstream climate impacts.

The assessment of impact cascades allows the identification of the climate impacts and action fields (sectors) that influence a particularly high number of other climate impacts. Furthermore, the assessment can be used to determine the highly influenced impacts and action fields.

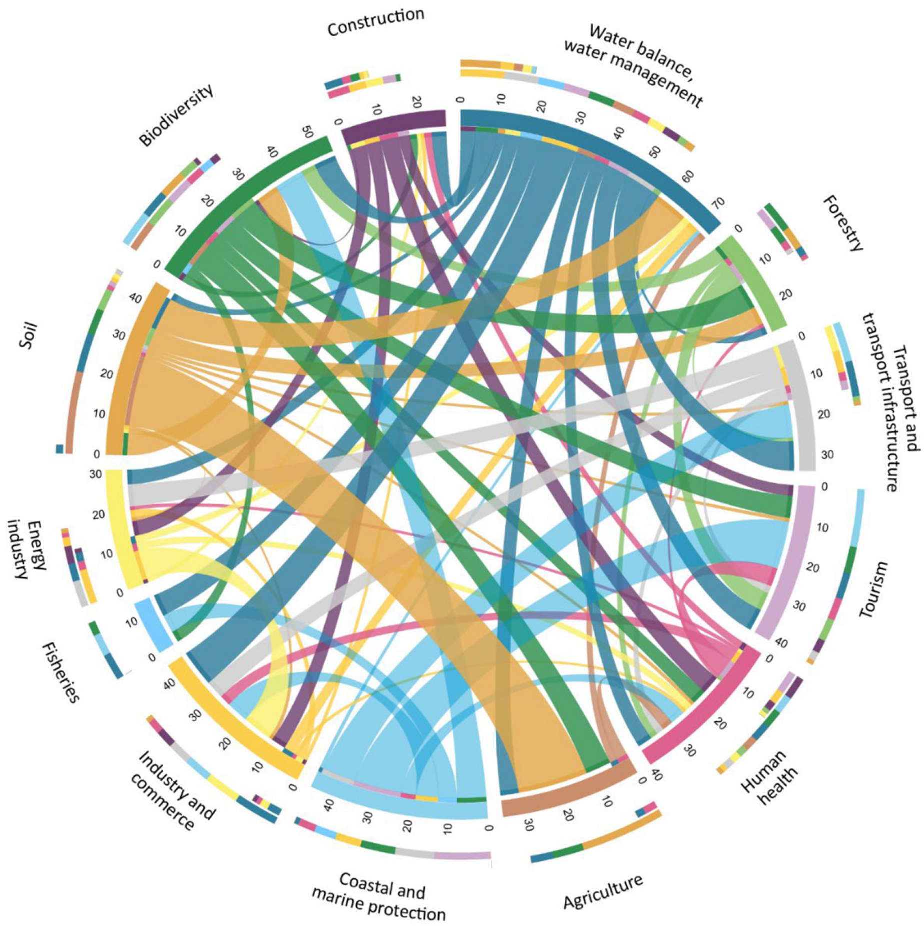
The interlinkages between climate impacts have already been analyzed as part of the last vulnerability assessment for Germany in 2015. For the CRA2021 the methodology was adapted and expanded. To provide a foundation for the analysis, the identification and description of interlinkages was part of the analysis of all 102 climate impacts. The possible linkages between sectors were highlighted in the introductory chapters of each action field (sector). The analysis of climate impacts was elaborated based on the impact chains developed for all the 13 sectors and additional desk research. The results were validated through expert workshops and several review processes with external experts.

	Present	Middle of Century (2031–2060) optimistic case	Middle of Century (2031–2060) pessimistic case	End of Century (2071–2100) optimistic case	End of Century (2071–2100) pessimistic case
Biodiversity	low	medium	medium-high	medium	high
Soil	low-medium	low-medium	medium-high	low-medium	medium-high
Agriculture	medium	medium	high	medium	high
Forestry	medium	medium	high	medium	high
Fisheries	low-medium	medium	high	medium	high
Coastal and marine protection	medium	medium	high	high	high
Water management, water balance	medium	medium	high	medium	high
Construction	medium	medium	medium-high	medium	high
Energy industry	low	low	low	low	low
Transport, transport infrastructure	low-medium	low	medium	low-medium	medium-high
Industry and commerce	medium	low	medium	low	medium
Tourism	low	low	medium	medium	high
Human health	medium	medium	high	medium-high	high

Source: Kahlenborn *et al*. 2021, p. 89

Figure 1. Overview of climate risk relevance without adaptation at the level of the action fields

For the integrated assessment and creation of impact cascades, the cross-references between individual climate impacts for each of the 102 climate impact chapters were identified through text analysis and then, recorded in a matrix table. Thus, the influencing and influenced climate impacts were determined (e.g. drought stress in forests influencing tree susceptibility to diseases/pests). The results were aggregated in the next step (at a sectoral level) and then, illustrated in a Circos plot (Figure 2).



Note: The thicknesses of the interlinkages indicate the number of interactions starting from the action field with the respective ring color. For example, there are many interactions from the "soil" action field that influence the action field "agriculture"
Source: Kahlenborn *et al*. (2021; p.93)

Figure 2. Interlinkages between different action fields (aggregate interlinkages between climate impacts)

Once all the impact chains are clearly determined and the causal relationships are identified, analyzing the cascade effects and the resulting aggregated risks is, in principle, relatively straightforward. Notably, the graphical representations of cascade effects can be effectively implemented in a visually appealing and easily understandable manner.

However, for a deeper understanding of specific cascade effects, a significant challenge lies in determining the influence of one impact chain on a subsequent chain, while considering all other input factors. Depending on whether the influence is at 5%, 10% or 20%, the causal relationships can range from relatively weak to significantly strong. When cascade effects occur across multiple impact chains, determining the exact extent of their influence is crucial. Moreover, when specific climate drivers simultaneously affect the interconnected impact chains, it is extremely difficult to estimate the significance of any changes in these climate drivers.

3.3.3 Hotspots of climate impacts. To describe the spatially heterogeneous situation in Germany, the CRA2021 used maps wherever possible. The maps portray the spatial patterns of climate change, exposure, vulnerability and climate risks for different time periods in a comparable manner. These maps also highlight the hotspots and thus, prove to be effective tools for communicating important information to the decision-makers and public. In addition to the aforementioned map products, CRA2021 developed an integrated analysis of climate-change information in the form of composite maps (Crespi *et al.*, 2023). This approach responds to the need to aggregate climate-related information into meaningful visualization products (Crespi *et al.*, 2023).

Climatic hotspot maps were compiled to evaluate the spatial patterns. The maps aimed to identify the areas in Germany that portray extreme values of the selected climatic drivers or high discrepancies between the present values and future projections.

The hotspot analysis was based on a cross-sector assessment of different climatic drivers. We chose the five climatic drivers, which negatively influenced the highest number of the climate impacts with a rating of "high" for current or future climate risks; these were: drought, heat, average precipitation decrease, average temperature increase and heavy rain. We observed that strong winds strongly influenced the climate risks rated high. However, owing to the lack of robust change signals in the projections for Germany, this driver was not included in the hotspot analysis. Hydrologic and oceanographic information were also excluded from the assessment.

To illustrate the climatic drivers, the following six indicators (three temperature-related and three precipitation-related) were defined:

(1) *Drought:* Number of dry days [daily sum of precipitation equal to 0 mm];

(2) *Heat:* Number of hot days [maximum daily temperature over 30°C], number of tropical nights [minimum temperature 20°C];

(3) *Average precipitation decrease:* Mean daily precipitation, 15th percentile [mm];

(4) *Average temperature increase:* Mean annual daily temperature [°C];

(5) *Heavy rain:* Number of days with heavy rain [daily sum of precipitation greater than 20 mm].

To consider the most extreme projections, we used the 15th and 85th percentiles of the climate model ensemble of the 30-year averages of the projected indicator values (under RCP8.5) for 2031–2060 and 2071–2100.

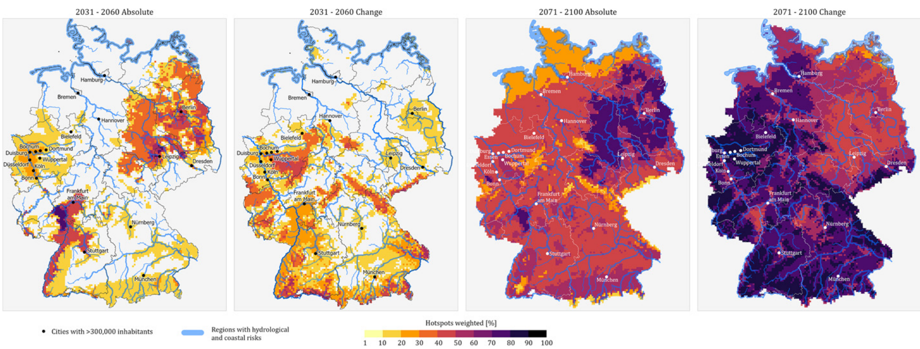
First, the hotspot maps for single indicators were created by extracting the pixels that exceeded the 85th percentile of the spatial distribution, representing 15% of the driest or warmest pixels. The values projected for 2031–2060 were used to derive the threshold values (Crespi *et al.*, 2023). The hotspot maps for single indicators were produced for 2031–2060 and 2071–2100 for both absolute values and relative changes) (Crespi *et al.*, 2023).

The six individual hotspot maps were aggregated, and weights were assigned to each indicator. The weights were based on the relevance of each indicator for the CRAs for 2031–2060 and 2071–2100. The weights were calculated by counting the climate risks in which the climate indicator featured (out of the total 102 risks assessed in this work) and multiplying the value by the evaluated risk level (with the values assigned for low, medium and high risk levels being 1, 2 and 3, respectively)(Crespi *et al.*, 2023).

The final hotspot maps represented the aggregated climate-change hotspots weighted by the evaluated risk level.

As climate impacts typically result from a multitude of factors, portraying the spatial representation of individual climate impacts at the national level is challenging. This challenge increases when multiple climate impacts are integrated and displayed on a single map. As demonstrated in Figure 3, the CRA2021 revealed a good methodological approach by considering the interlinkages between different climate drivers and the weighting of climate impacts. However, this approach presents another challenge. To achieve a spatial representation of the areas where the effects of climate change are particularly pronounced (referred to as “hotspots”), it is necessary to determine whether certain spatial units are disproportionately affected by changing climate drivers. To this end, it is important to differentiate between the absolute and relative changes that ultimately lead to specific impacts. Notably, both can be crucial in individual cases, and there are no general guidelines. The maps that are based on the changes in the climate drivers are therefore always subject to a certain degree of interpretation; to address this subjectivity, it would be important to determine whether the relative or absolute changes drive the aggregated climate impacts.

3.3.4 Integrating adaptive capacity. The assessment of adaptive capacity is one of the pillars of CRA2021 as it has been for other national CRAs (see Chapter 2 of this article). However, unlike many other CRAs adaptive capacity was already analyzed at the climate-impact level. Risk was assessed without climate adaptation, but also including climate-adaptation measures, thereby providing two different scenarios of adaptation. Notably, CRA2021 differentiated between two levels of adaptation: a) adaptation measures already adopted in the National Adaptation Plan (NAP) and b) a realistic set of more far-reaching adaptation (Kahlenborn *et al.*, 2021). The adaptation capacity was analyzed through literature review and the interviews of experts (Kahlenborn *et al.*, 2021). The adaptation capacity was subsequently evaluated using the Delphi method, i.e. via several consultation rounds, until a consensus was achieved among the experts (Kahlenborn *et al.*, 2021). Furthermore, the adaptive capacity for each action field (sector) was assessed, and ratings were assigned based on six dimensions: knowledge; motivation and acceptance; technology and natural resources; financial resources;



Notes: Left to right: (a) absolute; (b) change values for the middle of the century (2031–2060); (c) absolute; (d) change values for the end of the century (2071–2100)
Source: Adopted from Kahlenborn *et al*. (2021; p. 97)

Figure 3. Aggregated climate change hotspot maps

institutional structure and human resources; legal framework and political strategies (Kahlenborn *et al.*, 2021).

By further synthesizing the results of the individual and sectoral risk assessments, we determined the need for action in the event of severe climate change. This analytical step enabled recommendations with respect to the prioritization of adaptation measures, and clarified where planned and more far-reaching adaptation measures are sufficient to mitigate climate risks and where gaps are likely to remain (after the implementation of the adaptation measures). Moreover, statements on the potential for action could be made, on an abstract level, i.e. in terms of adaptation dimensions or categories of instruments that might be chosen to implement adaptation.

The prioritization of the climate risks and the adaptation needs was based on the risk scores (not considering adaptation) and the time needed for implementing adaptation measures as assessed for each risk. Based on a combination of these values, a distinction was possible between the risks that require (very) urgent action and those that do not.

As final step toward an integrated assessment of the results, the previously identified needs for action were characterized. The climate risks that required very urgent action were divided into five groups (drawing on the results of the analysis of adaptive capacity and the statements on the assessment certainties). These groups were distinguished based on the type and focal point of the adaptation measures to be implemented, e.g. the groups that focused on the adaptation measures already adopted or those that required further research to develop adaptation options, as shown below:

- *Implementation:* The planned adaptation measures are sufficient to reduce climate risk to a defined residual risk level. The focus is on the implementation of existing plans.
- *Development:* Planned adaptation measures are insufficient for reducing climate risk to a defined residual risk level. Therefore, far-reaching measures should be considered.
- *Development under uncertainty:* There is low certainty regarding the effectiveness of the adaptation measures; however, far-reaching measures may reduce climate risk to a defined residual risk level. Further research is recommended.
- *Innovation:* Planned and far-reaching adaptation measures are insufficient for reducing climate risk to a defined residual risk level. Therefore, transformative adaptation measures should be considered.
- *Innovation under uncertainty:* There is low certainty regarding the effectiveness of adaptation measures. Far-reaching adaptation measures may not be able to reduce climate risk to a defined residual risk level. Further research is recommended, particularly regarding possible transformative adaptation measures,

The methodological challenges in assessing the adaptive capacity partly resemble the challenges in evaluating individual climate impacts. However, adaptive capacity inherently results from a greater number of factors than the impacts caused by climate change alone. Each sensitivity factor, each exposure factor and in some cases even individual climate drivers can be influenced by different adaptation measures, resulting in a broad variety of factors. Consequently, any integrated analysis of adaptive capacity struggles to heavily abstract or simplify and streamline the assessment process. Within the framework of CRA2021, this goal was achieved reasonably, despite the pragmatic limitations described in this section.

Assessing adaptive capacity is crucial for conducting a comprehensive CRA. However, it is important to consider the substantial resources and time-commitment involved in conducting such assessments and understanding the necessity of simplifying the process.

4. Discussion

As mentioned at the beginning of this article, climate risk analyses are helpful for developing climate adaptation policies. They can provide scientifically justifications for climate adaptation measures and help policymakers to understand their impacts, thereby leading to better-informed decisions and improving resource allocation. Prioritizing climate-adaptation measures can be optimized using CRAs, and combined and holistic climate-adaptation strategies can be designed and implemented to target appropriate areas.

All these aspects also apply to CRA2021. In particular, the integrated assessment, a special component of CRA2021, contributes substantially toward fulfilling these functions. However, the various facets of integrated assessment have contributed to achieving the goals in different ways.

Our review suggests that the cross-sectoral analysis provides the greatest added value. As discussed in Chapter 2 regarding other national CRAs, similar experiences have been observed in other countries. The cross-sectoral analysis forms the basis for updating the national cross-sectoral climate-adaptation strategy, including the NAP. The collaborative setup of the climate risk analysis, which was necessary for the integrated cross-sectoral analysis, promoted cooperation among the national federal authorities involved in the field of climate adaptation. This has resulted in a shared understanding of the issues, risks and priorities, thereby creating better conditions for joint action at the political and administrative levels (wherever the related responsibilities overlap). The successful cross-sectoral cooperation and the integration of expert knowledge in CRA2021, especially for assessing vulnerability and adaptive capacity, also served as a model for setting up ISO 14091:2021.

The analyses of hotspots and cascading risks highlight the urgency of advancing climate-adaptation measures. These evaluations allowed us to visualize the important issues. The cascading-risk analysis also highlights the importance of natural systems in the overall context of climate-change impacts. The examination of the relationships across sectors and between individual impact chains was helpful in demonstrating that the effects of climate change propagate from natural to human-made systems, thereby highlighting the importance of stabilizing the natural systems themselves. The results of the hotspot analysis were incorporated into the design of a climate-adaptation funding program. This is also of great interest for subnational bodies who want to understand the spatial patterns of climate risks, journalists and the broader public.

For both types of analysis, hotspot and cascading risk analysis, it is also true that much better data would be necessary for many other important adaptation policy problems. This fact might explain why other national CRAs have thus far avoided hotspot analysis and allocated fewer resources to analyzing cascading effects. With regard to the hotspot analysis, data resolution is a major challenge, because only very-high resolution allows for usability of the data at the local level. Thresholds for each climate impact are also important for increasing the meaningfulness of spatial representation.

The integration of adaptive capacity into CRA2021 is a logical step, given the increasing knowledge about the risks associated with climate change. With the growing knowledge, establishing a direct link between CRAs and action planning becomes increasingly important as illustrated in Chapter 2 of this article. The integrated analysis of adaptive capacity within CRA2021 provides a better understanding of the timeframes required for adaptation. It also allows for the derivation of needs for action. The results of the CRA 2021 allow a gap analysis (similar to the UK gap analysis), to assess whether the most pressing climate risks are being addressed by current action planning. Similarly, the newly developed measurable targets of adaptation in the redesigned German national adaptation strategy are targeting climate risks which need urgent action.

Furthermore, by adding adaptive capacity to the integrated assessment, CRA2021 highlights the interconnections within the systems and improves system understanding. This clarifies how adaptation measures are interrelated and whether individual adaptation actions simultaneously influence different climate impacts. This, in turn, can be potentially valuable for action planning. For example, conflicts over water resources or land use were highlighted as important issues for climate adaptation in the CRA2021. They need to be addressed through better prioritization, for instance, within water or urban planning. In addition, the need for improved legislative frameworks and financial resources was taken up in further policy discussions.

For the future political reception of the CRA2021, it remains to be seen to what extent detailed results will influence the shaping of climate adaptation policy. In general, the fact that climate risk analyses are more problem-oriented than action-oriented hinders their political reception. The complexity of climate risk analysis does not make it easier for them to enter political discourse. Especially in the German context, and with regard to integrated assessments, the sectoral structure of individual central political units (especially federal ministries) responsible for the conceptualization and implementation of climate adaptation policy complicates the immediate adaptation of the analysis results into an integrated strategy. The extent to which this will succeed will be apparent only when the next national action plan for climate adaptation is developed.

5. Conclusion

Recent climate change-related events, such as the 2022 drought in Europe, demonstrate that major climate risks cannot be described or managed from a sectoral perspective only. Complex cascades of hazards and impact affect simultaneously different interlinked systems. Systemic risks, which emerge quickly, require a systemic perspective on risks and on possible solutions. Therefore, CRAs are important, which incorporate a cross-sectoral view, include hotspot analyses to reveal problem areas, identify cascades in impact chains and take adaptive capacity into account.

In practice, many national CRAs include cross-sectoral evaluations, which is highly relevant for prioritizing climate-adaptation measures priorities. Similarly, the inclusion of adaptation capacity increases, even if adaptive capacity is difficult to capture. Linking climate risks with the options available for mitigating these risks can provide a better picture of the resulting hazards and better characterizes needs for action. The analysis of cascading effects remains difficult and is included only to a smaller extent and only in few CRAs; furthermore, the majority of CRAs do not involve the identification of hotspots.

Regarding cascades of impacts, an interesting approach would be to study the complex interrelationships of the key compound risks in the past (e.g. the 2022 drought in Europe), to better understand the mechanisms of the key compound risks and identify the gaps and failures in risk management. Learning from past and current key compound risks can help focus on aspects that require a more in-depth integrated assessment.

Aspects that may have to be addressed in more detail in national CRAs include a better understanding of the interdependencies between climatic and non-climatic drivers, e.g. energy transition, urbanization, economic shocks or different crises situations (e.g. COVID-19 or the Ukraine war). This includes considering climate impacts outside Europe through supply chains, e.g. the impacts on global production and transport.

In the future, national CRAs will certainly move in the direction of adopting integrated approaches. The preconditions for CRAs are very different in individual countries, with respect to the objectives, existing knowledge, data availability, relevant climate signals, affected sectors and available resources. The development of a uniform approach for integrated assessments in CRAs is certainly impossible against this backdrop. There is no one-size-fits-all approach, nor is there a single best approach. However, it is possible to learn from the CRAs of other countries in developing each national approach. The European Union is actively promoting such exchange. Germany has benefited significantly from the work in Switzerland and the UK, with respect to the methodological design of CRA2021. This article can provide experts and policymakers the opportunity to benefit from the German experience (Table 1).

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